OPTIMAL COMBINATION OF ALTERNATIVE METHODS FOR SPATIAL FORECASTING IN PROBLEMS OF ATMOSPHERIC ECOLOGICAL MONITORING.
II. RESULTS OF NUMERICAL EXPERIMENTS

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This paper presents some results of numerical experiments on the estimation of the quality of spatial forecasting of vertical profiles of temperature and wind, carried out using the optimal combination of alternative methods (polynomial approximation, optimal extrapolation, and modified method of a clustering of arguments (MMCA)) as well as the data of aerological observations obtained for typical mesometeorological polygon. We exemplify that high precision of the forecast is typical for an algorithm based on the optimal combination of the method of optimal extrapolation and a modified version of the method of clustering of arguments. Insignificant errors resulted in this case allow its wide application in diagnosis and forecast of the atmospheric pollution level in the regions where no aerological data are available.

We can consider *a priori* that the spatial forecasting of mesometeorological fields, performed by means of a complex prognostic model,[1] will be much better than a forecast done on the basis of one of the alternative methods of extrapolation (polynomial approximation or optimal extrapolation) since this model takes into account not only the characteristics of horizontal structure of the field at different levels but also the dynamics of its variations. However, such an assumption needs, for its verification, certain numerical experiments on estimating the quality of corresponding forecasts. In this paper we consider some results of such experiments.

First of all, let us consider the characteristics of the initial data and some methodical aspects of forming the required sample of spatiotemporal observations. Since in our case we are dealing with a complex spatial forecasting in the problems of atmospheric ecological monitoring of local areas (for example, isolated region or industrial zone), the estimate of this forecast quality is made using, as an example, the vertical distribution of temperature and wind, being of considerable importance for the spread of pollutants.[2] Besides, in order to take into account the influence of the atmospheric mesoscale processes with horizontal scale from 20 km to 200 km on the forecast quality (Ref. 3), the paper presents the data from typical mesometeorological polygon. This polygon is represented by five aerological stations, namely, Nesterov (50°36′N, 23°56′E), Kovel' (51°11′N, 24°41′E), Kremenets (50°05′N, 25°41′E), Emel'chino (50°50′N, 27°46′E), and Chernovtsy (48°16′N, 25°55′E) located on the territory of western regions of Ukraine and Belorussia (the scheme of this polygon is shown in Fig. 1). In this case the data of field observations at all of the stations cover the period from November 24 till December 7, 1991 (the observations have been being done at 4 a.m. and 4 p.m., local time).

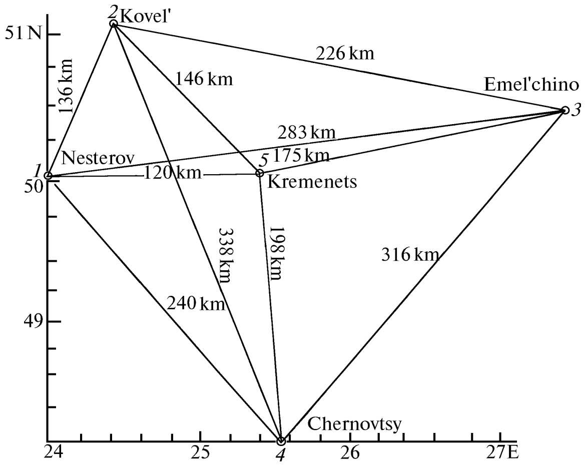

FIG. 1. The scheme of the polygon under consideration.

The fact should be noted here that all data of aerological observations are given in a single system of geometrical heights including nine standard levels: 0 (the ground level), 0.4, 0.8, 1.2, 1.6, 2, 4, 6, and 8 km, characterizing in detail not only the boundary atmospheric layer but practically all the troposphere where the transboundary transport of atmospheric pollutants takes place. Only the data of wind observations, because of the peculiarities of measurement equipment, are represented in a somewhat different system of geometrical heights, namely, 0.2, 0.4, 0.8, 1.2, 1.6, 2, 4, 6, and 8 km.

It is known[4] that for practical calculations of spread of a cloud of any impurity we usually use the level

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observations of temperature and wind and the data of their averaging over separate atmospheric layers. Therefore, for forming the array of initial data to be used for solving the problem we have performed a layer averaging of temperature T and zonal (U) and meridional (V) components of wind velocity, based on the data of observations of these physical parameters in the layers. The expressions used for averaging are[4]

$$<T>_{h_0\,,\,h} = \frac{1}{h - h_0} \int\limits_{h_0}^{h} T(z)\,\mathrm{d}z\;, \tag{1}$$

$$<U>_{h_0\,,\,h} = \frac{1}{h - h_0} \int\limits_{h_0}^{h} U(z)\,\mathrm{d}z\;, \tag{2}$$

$$<V>_{h_0\,,\,h} = \frac{1}{h - h_0} \int\limits_{h_0}^{h} V(z)\,\mathrm{d}z\;. \tag{3}$$

In the expressions (1)–(3) the angular brackets designate the altitude averaging in a certain layer $h_0 - h$ (here h_0 and h are the heights of the lower and the upper boundaries of the atmospheric layer under study). Normally, in practice of atmospheric ecological investigations, atmospheric layers calculated from the ground level, i.e., when $h_0 = 0$, are considered.

This fact was taken into account when calculating the average temperature $<T>$ and zonal $<U>$ and meridional $<V>$ components of the mean wind vector, whose values were used for estimating the quality of spatial forecasting. The estimate itself was performed by means of the rms error of such a forecast (E) and the error probability (P) (that is, deviations of the restored values of $<T>_{0-h}$, $<U>_{0-h}$, and $<V>_{0-h}$ from the corresponding actual values) being less than a certain value (for average temperature being less than ±1 ... ±4°C and more than ±4°C, and for the components of the mean wind velocity being less than ±1 ... ±4 m/s and more than ±4 m/s).

Let us now consider some results of numerical experiments on estimating the quality of spatial forecasting of the ground (T_0) and average ($<T>_{0-h}$) temperature and components of the mean wind vector ($<U>_{0-h}$ and $<V>_{0-h}$) carried out using the methods of polynomial approximation and optimal extrapolation as well as using an optimal complex algorithm. In so doing let us first analyze the results of statistical evaluation of the forecast quality, performed by the method of polynomial approximation or optimal extrapolation. Let us also consider a possibility of choosing the best (from the standpoint of accuracy of spatial forecast) method. For this purpose let us make use of Tables I–III, containing the values of the error probability (P) of restoration of the ground (T_0) and average ($<T>_{0-h}$) temperature being less than ±1 ... ±4°C and more than ±4°C as well as the errors of restoration of the mean wind components ($<U>_{0-h}$ and $<V>_{0-h}$) being less than ±1 ... ±4 m/s and more than ±4 m/s.

Let us note at the very beginning that because of a large bulk of material, given in Tables I–III, as an example are the results of precise estimates only for two typical stations of the polygon under study, i.e., Nesterov and Kovel'.

Numerical experiments on evaluation of the quality of spatial forecast performed by the methods of polynomial and optimal extrapolation individually, have shown that:

– the best results of such a forecast (whatever the method used) are characteristic of the ground temperature and the components of the mean wind vector in the layer of 0.2–0.4 km. For example, the probability of spatial forecast (reconstruction) of ground temperature by the optimal extrapolation method with the error less than ±1°C is 0.63–0.88, and with the error less than ±2°C, i.e., less than the error value, permitted by the International Meteorological Organization for radiosonde observations,[5] the probability of spatial forecast is already 0.94;

– from the components of the mean wind vector the meridional component is predicted most efficiently, for which the probability of the forecast errors, performed by the same method, less than ±1 m/s is 0.66–0.88;

– the method of optimal extrapolation gives higher accuracy of spatial forecast for temperature fields and components of mean wind vector than the method of polynomial extrapolation that is clear from Table IV.

An important factor is that the maximum increase of the probabilities of restoration by the optimal extrapolation method, as it follows from Table IV, is for the error values ≤ ±1°C and ±1 m/s.

TABLE I. Values of probabilities (P) of errors of temperature restoration being less than ±1 ... ±4°C and more than ±4°C obtained by the method of polynomial (a) and optimal (b) extrapolation for the stations Nesterov (1) and Kovel' (2).

Layer, km	Probability, P																			
	≤ ±1°C				≤ ±2°C				≤ ±3°C				≤ ±4°C				> ±4°C			
	1		2		1		2		1		2		1		2		1		2	
	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b
0	0.44	0.63	0.31	0.88	0.78	0.94	0.81	0.94	0.81	0.94	0.90	1.00	0.94	1.00	1.00	1.00	0.06	0	0	0
0–0.4	0.50	0.50	0.06	0.31	0.75	0.81	0.25	0.88	0.88	0.81	0.69	0.94	0.88	0.94	0.75	0.95	0.13	0.06	0.25	0.05
0–0.8	0.38	0.19	0.13	0.19	0.69	0.69	0.19	0.69	0.75	0.88	0.38	0.88	0.88	0.94	0.56	0.94	0.13	0.06	0.44	0.06
0–1.2	0.38	0.25	0.13	0.25	0.56	0.63	0.19	0.44	0.75	0.88	0.25	0.75	0.88	0.88	0.50	0.88	0.13	0.13	0.50	0.13
0–1.6	0.38	0.19	0.06	0.19	0.56	0.50	0.19	0.50	0.69	0.88	0.25	0.69	0.88	0.88	0.38	0.81	0.13	0.13	0.63	0.19
0–2	0.31	0.19	0.06	0.25	0.56	0.56	0.06	0.50	0.69	0.88	0.19	0.63	0.88	0.88	0.31	0.81	0.13	0.13	0.69	0.19
0–4	0.19	0.25	0.06	0.19	0.44	0.38	0.13	0.38	0.75	0.75	0.13	0.50	0.81	0.88	0.25	0.75	0.19	0.13	0.75	0.25
0–6	0.19	0.13	0.06	0.19	0.44	0.44	0.13	0.31	0.75	0.69	0.13	0.50	0.81	0.81	0.19	0.63	0.19	0.19	0.81	0.38
0–8	0.19	0.13	0.06	0.19	0.44	0.44	0.13	0.31	0.75	0.69	0.13	0.50	0.81	0.81	0.25	0.69	0.19	0.19	0.75	0.31

TABLE II. Values of probabilities (P) of errors of restoration of wind zonal component being less than ±1 ... ±4 m/s *and more than* ±4 m/s, *obtained by the method of polynomial (a) and optimal (b) extrapolation for the stations Nesterov (1) and Kovel' (2).*

Layer, km	Probability, *P*																			
	≤ ±1 m/s				≤ ±2 m/s				≤ ±3 m/s				≤ ±4 m/s				> ±4 m/s			
	1		2		1		2		1		2		1		2		1		2	
	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b
0.2–0.4	0.31	0.56	0.19	0.45	0.50	0.75	0.44	0.66	0.78	0.88	0.65	0.75	0.79	0.88	0.74	0.79	0.21	0.13	0.26	0.21
0.2–0.8	0.13	0.38	0.13	0.29	0.31	0.56	0.19	0.35	0.38	0.63	0.38	0.50	0.50	0.69	0.44	0.54	0.50	0.31	0.56	0.46
0.2–1.2	0.13	0.38	0.06	0.13	0.25	0.38	0.13	0.19	0.25	0.56	0.19	0.19	0.31	0.56	0.31	0.35	0.69	0.44	0.69	0.65
0.2–1.6	0.19	0.31	0.06	0.13	0.25	0.38	0.06	0.19	0.25	0.50	0.13	0.19	0.31	0.50	0.19	0.19	0.69	0.50	0.81	0.81
0.2–2.0	0.19	0.25	0.06	0.06	0.25	0.31	0.06	0.19	0.31	0.38	0.13	0.19	0.31	0.50	0.13	0.19	0.69	0.50	0.88	0.81
0.2–4.0	0.19	0.19	0.06	0.06	0.25	0.25	0.06	0.13	0.31	0.31	0.13	0.19	0.31	0.44	0.13	0.19	0.69	0.56	0.88	0.81
0.2–6.0	0.25	0.13	0.06	0.06	0.25	0.19	0.13	0.13	0.31	0.25	0.13	0.13	0.31	0.25	0.19	0.19	0.69	0.75	0.81	0.81
0.2–8.0	0.19	0.13	0.06	0.06	0.25	0.13	0.13	0.13	0.31	0.19	0.13	0.13	0.38	0.25	0.31	0.19	0.63	0.75	0.69	0.81

TABLE III. Values of probabilities (P) of restoration errors of meridional component of the wind being less than ±1 ... ±4 m/s *and more than* ±4 m/s, *obtained by the method of polynomial (a) and optimal (b) extrapolation for stations Nesterov (1) and Kovel' (2).*

Layer, km	Probability, *P*																			
	≤ ±1 m/s				≤ ±2 m/s				≤ ±3 m/s				≤ ±4 m/s				> ±4 m/s			
	1		2		1		2		1		2		1		2		1		2	
	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b
0.2–0.4	0.56	0.66	0.63	0.88	0.95	1.00	0.94	1.00	0.98	1.00	0.98	1.00	1.00	1.00	1.00	1.00	0	0	0	0
0.2–0.8	0.25	0.35	0.31	0.56	0.50	0.66	0.63	0.88	0.69	0.76	0.75	0.88	0.94	1.00	0.94	1.00	0.06	0	0.06	0
0.2–1.2	0.13	0.19	0.19	0.38	0.31	0.38	0.31	0.63	0.56	0.63	0.63	0.75	0.69	0.69	0.69	0.88	0.31	0.31	0.31	0.13
0.2–1.6	0.13	0.13	0.13	0.31	0.31	0.44	0.25	0.63	0.44	0.56	0.56	0.63	0.56	0.69	0.63	0.75	0.44	0.31	0.38	0.25
0.2–2.0	0.06	0.19	0.13	0.31	0.31	0.38	0.19	0.63	0.44	0.50	0.50	0.63	0.56	0.63	0.63	0.75	0.44	0.38	0.38	0.25
0.2–4.0	0.06	0.19	0.13	0.44	0.19	0.38	0.19	0.63	0.38	0.50	0.38	0.63	0.56	0.63	0.63	0.69	0.44	0.38	0.38	0.31
0.2–6.0	0	0.13	0.13	0.38	0.13	0.25	0.25	0.50	0.44	0.50	0.38	0.63	0.56	0.69	0.50	0.69	0.44	0.31	0.50	0.31
0.2–8.0	0	0	0.13	0.38	0.19	0.31	0.31	0.44	0.31	0.38	0.38	0.63	0.50	0.63	0.44	0.69	0.50	0.38	0.56	0.31

TABLE IV. Values of increase in the probability (P) of errors of spatial forecast of the near ground temperature being less than ±1 ... ±3°C *and the components of the mean wind vector less than* ±1 ... ±3 m/s, *performed by the method of optimal extrapolation, as compared with the probability of the same errors obtained using the method of polynomial approximation.*

Level (layer) of minimal error of the forecast, km	Probability, *P*					
	≤ ±1°C or ≤ ±1 m/s		≤ ±1°C or ≤ ±1 m/s		≤ ±1°C or ≤ ±1 m/s	
	Nesterov	Kovel'	Nesterov	Kovel'	Nesterov	Kovel'
Near ground temperature						
0	0.19	0.57	0.16	0.13	0.13	0.10
Zonal component of the mean wind vector						
0.2–0.4	0.25	0.26	0.25	0.22	0.10	0.11
Meridional component of the mean wind vector						
0.2–0.4	0.10	0.25	0.05	0.06	0.02	0.02

Due to the advantages of the method of optimal extrapolation (over polynomial approximation), this method was used in the complex procedure together with the method of clustering of arguments.

Let us consider the results of statistical estimate of the quality of reconstruction of the altitude structure of fields of temperature and wind conducted on the basis of combining the optimal extrapolation method with a modified version of MMCA. For this purpose we used the results of spatial forecast of temperature and wind at the level or in the layer of minimal error (for temperature this is the ground level and for the mean wind components this is the 200–400 m atmospheric layer), performed by the optimal extrapolation method, and also the spatiotemporal observations carried out at one of the reference stations nearest to the point sought.

The results of statistical estimate of the quality of spatial forecast of temperature and wind, carried out by means of a complex algorithm, are given in Tables V–VII. For the two stations mentioned above these tables give standard (rms) errors of restoration (E) and probability (P) of the errors of the forecast, being less than ±1 ... ±4°C and more than ±4°C for average temperature and less than ±1 ... ±4 m/s and more than 4 m/s for the components of the mean wind vector.

Analysis of the data from Tables V–VII and comparison of these with the data from Tables I–III show that the complex approach to solution of the problem of spatial forecast of vertical structure of meteorological fields based on combining of two alternative methods (the optimal extrapolation method and MMCA) is rather efficient since in its use, first, one can essentially improve (as compared with the optimal extrapolation method) the quality of the spatial forecast of meteorological parameters under study; second, one can significantly increase (as compared with the optimal extrapolation method) the peak of reliable restoration of the average temperature and components of the mean wind vector. In particular, this follows from the fact that large values of the probability ($P \geq 0.60$) of restoration errors $\langle T\rangle_{0-h}$ being less than ± 2°C and $\langle U\rangle_{0-h}$ and $\langle V\rangle_{0-h}$ being less than ± 2 m/s are typical not only for the lower layer (this is observed when using the optimal extrapolation method), but also for the entire tropospheric layer under study.

TABLE V. Standard errors (E) and probabilities (P) of errors of restoration of average temperature being less than ±1 ... ±4°C *and more than* ±4°C, *obtained by means of optimal extrapolation and MMCA at the stations Nesterov (1) and Kovel' (2).*

Layer of restoration, m	Probability, *P*										*E*	
	≤ ±1°C		≤ ±2°C		≤ ±3°C		≤ ±4°C		> ±4°C			
	1	2	1	2	1	2	1	2	1	2	1	2
0–400	0.40	0.80	0.75	0.90	1.00	1.00	1.00	1.00	0	0	1.5	1.0
0–800	0.35	0.70	0.65	0.95	0.95	1.00	1.00	1.00	0	0	1.9	1.1
0–1200	0.30	0.65	0.60	0.90	0.90	0.95	0.95	1.00	0.05	0	2.1	1.4
0–1600	0.25	0.70	0.60	0.85	0.85	0.95	0.95	1.00	0.05	0	2.3	1.4
0–2000	0.25	0.55	0.60	0.80	0.85	0.95	0.90	0.95	0.10	0.05	2.3	1.5
0–4000	0.20	0.35	0.50	0.80	0.75	0.95	0.80	1.00	0.20	0	2.9	1.7
0–6000	0.20	0.25	0.50	0.75	0.75	0.95	0.80	0.95	0.20	0.05	2.9	1.9
0–8000	0.25	0.20	0.60	0.65	0.75	0.90	0.80	0.95	0.20	0.05	2.8	2.0

TABLE VI. Standard errors (E) and probabilities (P) of errors of restoration of zonal component of mean wind velocity being less than ±1 ... ±4 m/s *and more than* ±4 m/s *obtained by means of optimal extrapolation and MMCA at the stations Nesterov (1) and Kovel' (2).*

Layer of restoration, m	Probability, *P*										*E*	
	≤ ±1 m/s		≤ ±2 m/s		≤ ±3 m/s		≤ ±4 m/s		> ±4 m/s			
	1	2	1	2	1	2	1	2	1	2	1	2
200–800	0.55	0.35	0.70	0.65	0.90	0.75	0.95	0.85	0.05	0.15	2.1	2.5
200–1200	0.70	0.45	0.75	0.70	0.95	0.85	0.95	1	0.05	0	1.7	2.0
200–1600	0.65	0.45	0.75	0.80	1	0.95	1	1	0	0	1.4	1.7
200–2000	0.70	0.60	1	0.80	1	1	1	1	0	0	0.9	1.4
200–4000	0.70	0.60	0.95	0.70	1	0.80	1	1	0	0	1	1.9
200–6000	0.60	0.55	0.85	0.65	1	0.80	1	0.90	0	0.10	1.3	2.1
200–8000	0.75	0.55	1	0.60	1	1	1	1	0	0	0.9	1.8

TABLE VII. Standard errors (E) and probabilities (P) of the errors of restoring the meridional component of the mean wind velocity less than ±1 ... ±4 m/s *and more than* ±4 m/s, *obtained using the optimal extrapolation and MMCA at the stations Nesterov (1) and Kovel' (2).*

Layer of restoration, m	Probability, *P*										*E*	
	≤ ±1 m/s		≤ ±2 m/s		≤ ±3 m/s		≤ ±4 m/s		> ±4 m/s			
	1	2	1	2	1	2	1	2	1	2	1	2
200–800	0.45	0.65	0.65	0.95	1	1	1	1	0	0	1.7	1.6
200–1200	0.40	0.70	0.65	1	0.95	1	1	1	0	0	1.9	1
200–1600	0.40	0.70	0.70	1	0.95	1	1	1	0	0	1.9	1
200–2000	0.35	0.70	0.80	1	0.95	1	0.95	1	0.05	0	1.7	0.9
200–4000	0.30	0.60	0.65	0.90	0.95	1	1	1	0	0	2	1.5
200–6000	0.30	0.60	0.65	0.90	0.95	1	1	1	0	0	2.2	1.8
200–8000	0.35	0.65	0.70	1	0.95	1	1	1	0	0	2	1.6

Thus, as the results of numerical experiments have demonstrated, the use of a combination of two methods (optimal extrapolation and MMCA), when solving the problem of spatial forecast of the mesoscale fields of temperature and wind, is very promising.

Therefore, this approach can be successfully used in the problems of numerical estimate of spatial spread of pollutants in regions where no data of aerological observations along the path of this spread are available.

In conclusion it should be noted that the obtained results call for additional check on the basis of a more complete statistical material. However, this problem is the subject of our further research.

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