Automated meteorological system for fast processing of aerological information, diagnostics, and forecasting the atmospheric state on mesoscales. Part 2. Performance tests of the system

V.S. Komarov, A.Ya. Bogushevich, S.N. Il'in, A.V. Kreminskii, Yu.B. Popov, and A.I. Popova

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

Received December 10, 2004

We discuss the results of approbation and statistical assessment of the quality of algorithms that have been employed by the automated meteorological system for forecasting, in space and time, mesoscale fields of meteorological quantities (geopotential, temperature, and the orthogonal components of the wind velocity).

In Ref. 1 we have considered the structure, the initial algorithms used, and performance parameters of the automated meteorological system (AMS), which has been developed at the Institute of Atmospheric Optics, Siberian Branch of the Russian Academy of Sciences. However, its efficiency and practical value are the questions to be addressed yet.

Just these questions make up the subject of this paper, which continues the discussion presented in Ref. 1. To achieve the goal we have assessed, based on experimental data available, the quality and efficiency of algorithms employed by the AMS. To do this, we have performed its approbation by forecasting the state of the atmosphere and demonstrate the results in a graphical form. Also, we have determined statistical characteristics of the success or warranty of the numerical diagnostics and forecast of the state of the atmosphere. Note that we consider the task of making diagnostics of the state of the atmosphere over a territory not covered by meteorological observations by use of the data acquired in the adjacent regions as the task of mesoscale spatial extrapolation (or interpolation) of the meteorological fields.

1. Initial data and some aspects of the statistical assessment of the quality of AMS algorithms

To approbate the AMS algorithms and to assess statistically their quality, we made use of the data of perennial (2000 – 2003) two-term (at 00 and 12 h GMT) observations at five aerological stations. Those were Moscow (55°45′N, 37°57′E), Ryazan (54°38′N, 39°42′E), Sukhinichi (54°06′N, 35°21′E), Smolensk (54°45′N, 32°04′E), and Kursk (51°46′N, 36°10′E). These stations make up a typical mesometeorological polygon.

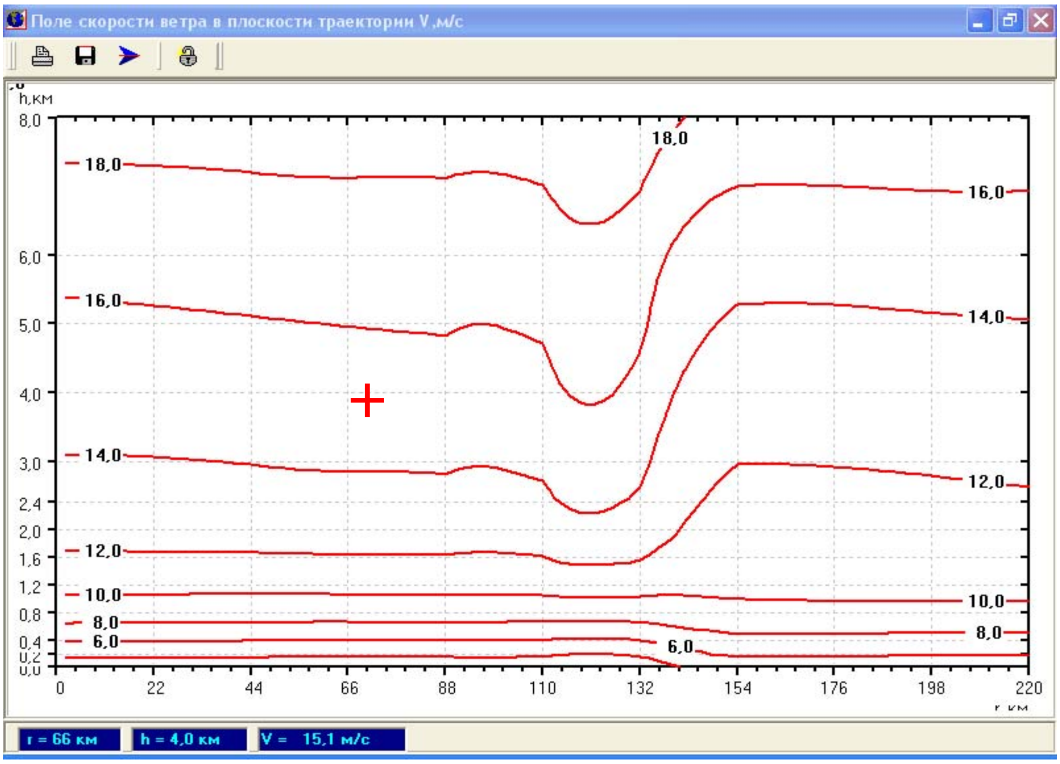
To make a statistical assessment of the quality of AMS algorithms we have selected only synchronous two-term observations at all the stations from the entire array of the initial data presented in the form of KN-4 bulletins. Then these data were either reduced [using linear interpolation (see Eq. (1) in Ref. 1) made with the account of information at singular points] to the coordinate system of standard heights, i.e., at 0 (ground level), 0.2, 0.4, 0.8, 1.2, 1.6, 2.0, 2.4, 3.0, 4.0, 5.0, 6.0, and 8.0 km, or taken without the reduction at six standard isobaric surfaces of 925, 850, 700, 500, 400, and 300 hPa. In this case the total number of realization was about 200 for each type of the data.

Consider now some methodological aspects of the statistical assessment of the quality of the algorithms used in the AMS for numerical diagnostics and forecasting.

In practice, the assessment of the extrapolation (interpolation) quality is being done in a simple way by finding the value of a meteorological quantity at some control station using data acquired at the neighbor stations avoiding its calculation at this point or at the nodes of a regular grid.[2] The differences between the extrapolated (interpolated) and actual values of the parameters make up the basis for the assessment of the forecast quality by use of one or another statistical characteristic of its efficiency. Similar technique has been used in this study too. In our assessments of the quality of the numerical algorithms developed for diagnostics and forecasting we have used the standard, i.e., the rms, δ_ξ, and relative, θ_ξ, %, errors calculated by the following formulas

0235-6880/05/08 635-07 $02.00

The resultant wind speed



The direction of the resultant wind

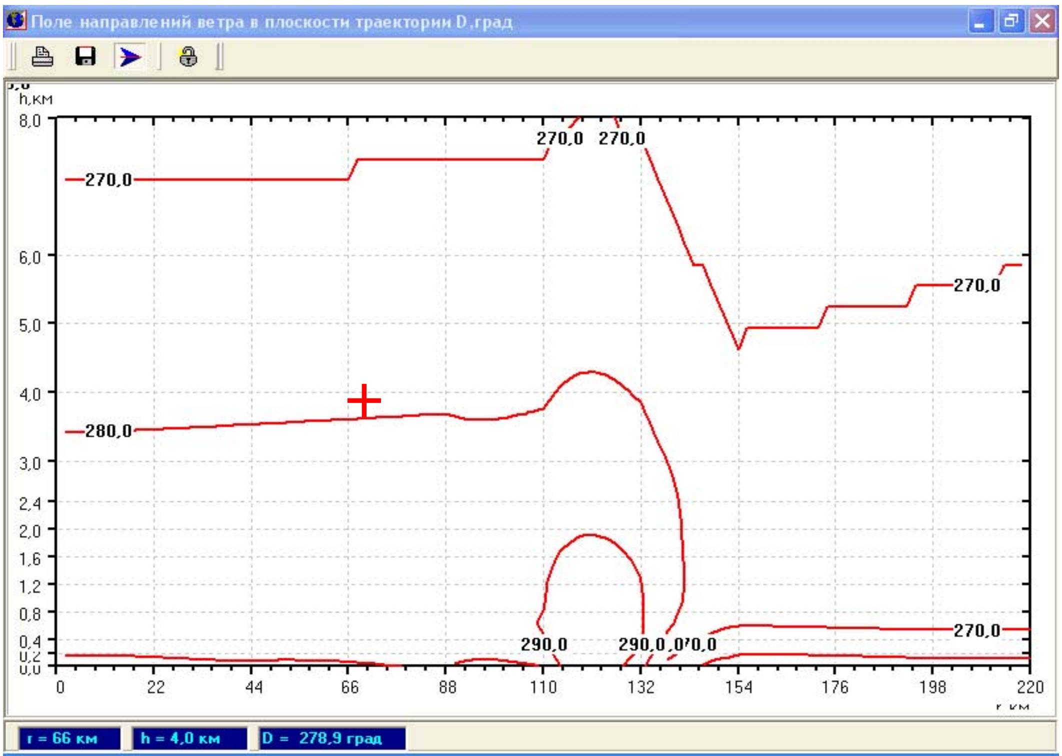
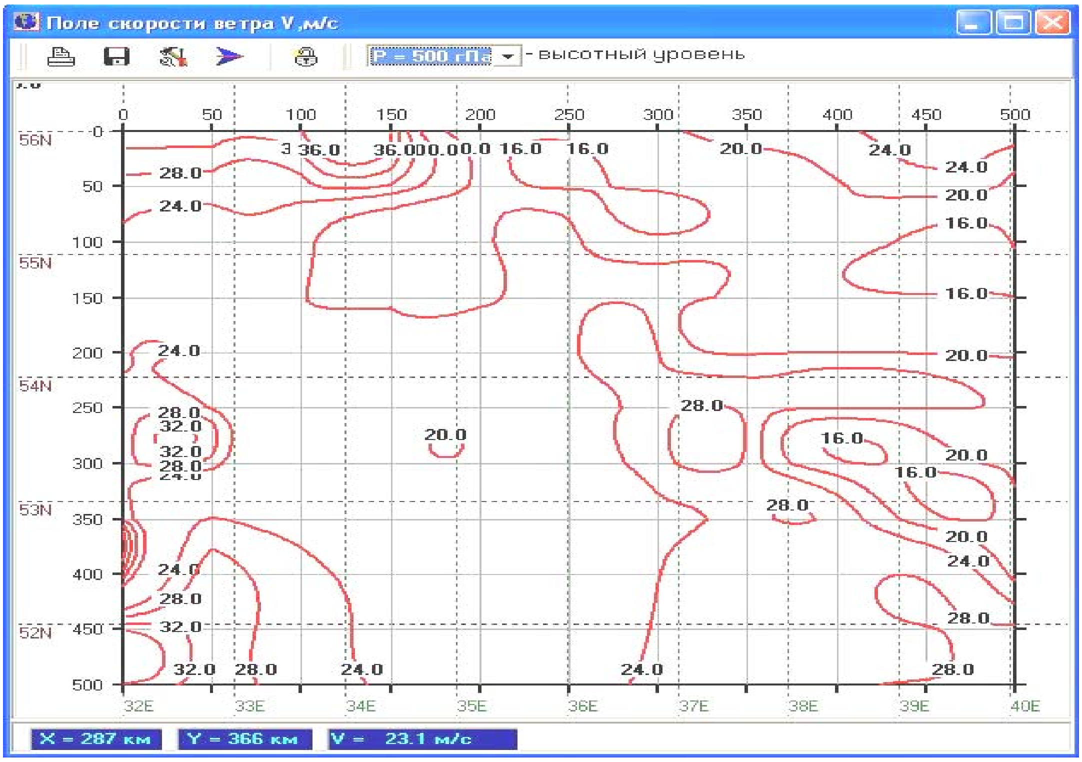


Fig. 1. An example of the spatial extrapolation of the wind field along a preset trajectory to the distance of 225 km; August 17, 2003, 00 h GMT according to data collected on the mesoscale polygon with the center in Station Sukhinichi.

Wind velocity field



The field of wind direction

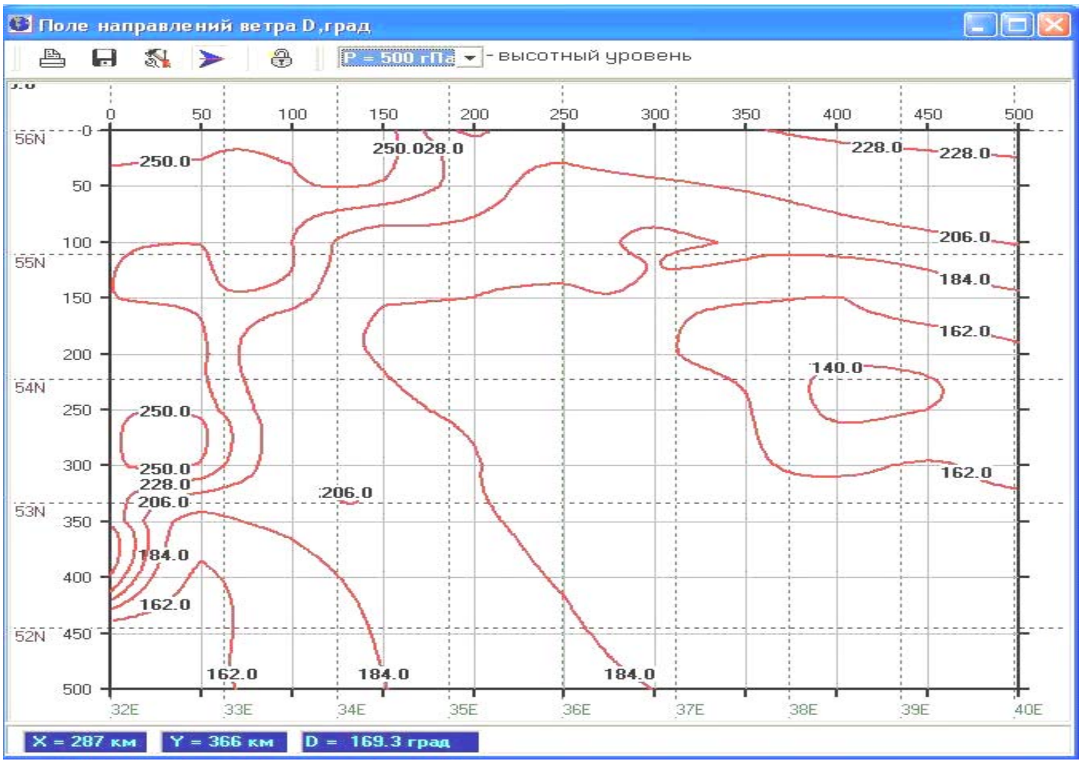


Fig. 2. An example of the objective analysis of the wind field on the isobaric surface of 500 hPa performed by the system for the day of July 17, 2001, at 12 h GMT according to data collected on the mesoscale polygon with the center in Station Sukhinichi.

$$\delta_{\xi_j} = \left[\frac{1}{n_j} \sum_{i=1}^{n_j} (\hat{\xi}_{ij} - \xi_{ij})^2 \right]^{1/2}; \quad (1)$$

$$\theta_{\xi_j} = \delta_{\xi_j} / \sigma_{\xi_j}, \quad (2)$$

where $\hat{\xi}_{ij}$ and ξ_{ij} are the prognostic, i.e., obtained by spatial interpolation (extrapolation) or by use of forecasting in time and the value of the meteorological quantity measured at the control point at the forecast time from the ith realization at the jth level; n_j is the number of the realizations at the jth level used, and σ_{ξ_j} is the standard deviation of the meteorological quantity at the jth level.

In addition to the standard error we also used the probability P of the errors in forecasting the state of the atmosphere, which exceed or are below a preset value ($\Delta_i \le \pm 1, ..., \le \pm 4$ and $\Delta_i > \pm 4$°C for temperature and $\Delta_i \le \pm 1, ..., \le \pm 4$, and $\Delta_i > \pm 4$ m/s for the orthogonal components of the wind velocity).

In conclusion of this section it is worthy to note that in statistical assessment of the quality of algorithms of spatial extrapolation applied to temperature and wind, which, e.g., play an important role in the spread of a pollution plume from its source,[3] we used not the values of meteorological quantities measured at the height levels, but their values averaged over some layers in the atmosphere. To calculate the average values of temperature $\langle T \rangle_{h_0,h}$, zonal $\langle V_x \rangle_{h_0,h}$ and meridional $\langle V_y \rangle_{h_0,h}$ wind components, we used the expression (3) from Ref. 1.

2. Examples of approbation of the AMS algorithms using data of actual aerological measurements

Prior to analyzing the results of statistical assessment of the quality of the diagnostics and forecasting algorithms used in the AMS we shall present some examples of approbation of the algorithms that has been carried out based on real aerological information.

Figure 1 presents an example of the spatial extrapolation of the wind velocity field along a preset trajectory to the distance of 225 km from the nearest aerological station capable of making wind profiling. The data have been collected on August 17, 2003 at 00 h GMT at four stations, namely, Moscow, Ryazan, Sukhinichi, and Kursk.

It is worth noting that first, the spatial extrapolation itself has been carried out of the zonal and meridional components of the wind velocity and only then the extrapolation of the resultant wind speed and direction was performed. Thus obtained results are depicted in Fig. 1. The extrapolation has been done using expressions from Ref. 3:

$$V_r = \sqrt{V_x^2 + V_y^2}; \quad (3)$$

$$D_r = \arctan(V_x / V_y), \quad (4)$$

where V_r and D_r are the speed and direction of the resultant wind velocity; V_x and V_y are the zonal and meridional components of the wind.

Besides, it ought to be noted that in order to draw isovels and isogonic lines, that is, the lines of equal speed and same wind directions,[4] the initial prognostic data have been taken with the 1-km horizontal resolution and 20-m height resolution.

The second example of the AMS algorithms approbation presents the data of objective analysis of the wind field on the isobaric surface of 500 hPa (Fig. 2) carried out based on the data acquired on July 17, 2001 (12 h GMT) at all the five stations mentioned above. The stations are located within the mesoscale polygon chosen with its center in Sukhinichi. As in the case of spatial extrapolation the objective analysis was, first, applied to zonal and meridional components of the wind. The interpolated values of these fields were then used to draw the maps of isovels and isogonic lines shown in Fig. 2. It is worth noting that the prognostic data used for mapping have been calculated with 1 × 1 km spatial resolution. This enabled us to obtain well smoothed isolines of the resultant wind speed and direction.

Finally, the third example of the AMS algorithms testing is an example of very-short-term forecast (3 to 6 hours lead time) of the temperature value near the ground surface performed on May 14–15, 2003 in the suburbs of Tomsk based on the data acquired with an AMK-03 acoustic system in 20-minute intervals. Figure 3 presents a comparison between the forecast and measurement data on air temperature.

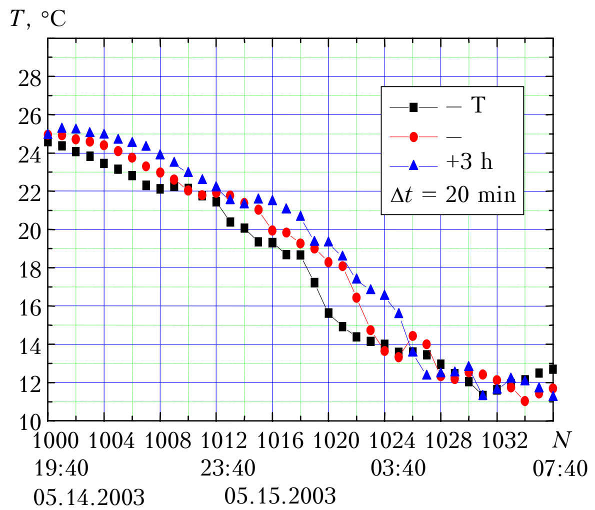


Fig. 3. An example of the temperature forecast with the lead time of 3 and 6 hours based on data acquired with AMK-03 on May 14–15, 2003 in the suburbs of Tomsk (local time).

3. Results of statistical assessment of the quality and efficiency of the prognostic algorithms employed by the automated meteorological system

Let us now pass to analysis of the results obtained in statistical assessment of the quality of spatial extrapolation algorithms, objective analysis, and very-short-term forecast used at the development of the automated meteorological system.

3.1. Assessment of the quality of the spatial extrapolation algorithms

Consider, first, analysis of the results on the quality of the spatial extrapolation algorithm used in the AMS for averaging the temperature, zonal and meridional wind components over a layer in the atmosphere over a territory not covered with observations. Let us note from the very beginning that these parameters are widely used in numerical diagnostics of the pollution cloud dispersal, as well as in the practice of the military geophysics.

It is also worth reminding here that the algorithms of spatial extrapolation we made use of in the AMS are based on Kalman filtering apparatus and on a few-parameter dynamic-stochastic model, which accounts for correlation properties of the fields of meteorological quantities.

In Table 1 we present the results on statistically assessed quality of algorithms of spatial extrapolation of the layer-mean values of temperature and zonal and meridional components of the wind velocity. The results are presented in the form of standard (rms) error δ_ξ and by the probability P that the errors of such an extrapolation are below or exceed some preset value. Let us also underline that the data given in Table 1 present an example of the results on statistical assessment of the algorithm used only for the case of winter season and control station of Smolensk, which is 225 km to the west from Sukhinichi station, where the data of aerological observations are available. Hence, we consider an extreme case of extrapolating data, which is being done in the direction opposite to the direction of the prevailing easterly air mass transport characteristic of the winter atmosphere in the midlatitudes of the northern hemisphere.[5]

Analysis of the data presented in Table 1 shows that:

– the algorithm of the spatial extrapolation, used for forecasting the layer-mean temperature and the orthogonal components of the wind velocity to the distance of up to 225 km gives quite reliable results because, independent of the layer, the standard errors are within the limits of 1.2–1.5°C for $<T>_{h_0,h}$ and 1.0–2.0 m/s for the $<V\text{x}>_{h_0,h}$ and $<V_\text{x}>_{h_0,h}$ parameters and the probability of errors of such an extrapolation is about 0.84 to 0.86 at $\Delta T \le \pm 2$°C and 0.76–0.95 at ΔV_x, $\Delta V_y \le \pm 2$ m/s;

– standard errors in the layer-mean values of the zonal and meridional components of the wind velocity equal to 1.0 to 2.0 m/s throughout the tropospheric layer considered are comparable with the rms errors of wind velocity measurements with radiosondes, which vary, according to Ref. 6, from 0.9 to 2.0 m/s.

Table 1. Standard errors δ_ξ and probabilities of the errors in the spatial extrapolation of the layer-mean values of temperature ($\Delta_i \le \pm 4$°C and $\Delta_i > \pm 4$°C), zonal and meridional components of the wind velocity ($\Delta_i \le \pm 4$ m/s and $\Delta_i > \pm 4$ m/s) to the distance of 225 km made using the automated meteorological system. Winter

Layer, km	$P \cdot 10^2$					δ_ξ
	$\Delta_i \le \pm 1$	$\Delta_i \le \pm 2$	$\Delta_i \le \pm 3$	$\Delta_i \le \pm 4$	$\Delta_i > \pm 4$	
	Temperature,°C					
0–0.2	73	86	91	96	04	1.2
0–0.4	71	85	91	96	04	1.3
0–0.8	70	85	91	96	04	1.4
0–1.2	67	84	91	96	04	1.5
0–1.6	66	84	91	96	04	1.5
0–2.0	65	84	91	96	04	1.5
0–2.4	64	84	91	96	04	1.5
0–3.0	65	84	91	97	03	1.5
0–4.0	68	84	91	97	03	1.5
0–5.0	68	84	91	97	03	1.5
0–6.0	68	84	93	97	03	1.5
0–8.0	68	84	96	98	02	1.4
	Zonal component of the wind velocity, m/s					
0–0.2	77	94	98	99	01	1.1
0–0.4	74	90	95	99	01	1.3
0–0.8	71	86	91	97	03	1.5
0–1.2	67	85	90	96	04	1.6
0–1.6	62	85	90	95	05	1.7
0–2.0	56	83	90	95	05	1.8
0–2.4	54	82	90	94	06	1.8
0–3.0	54	81	90	94	06	1.8
0–4.0	54	81	90	94	06	1.8
0–5.0	57	80	90	94	06	1.8
0–6.0	57	80	90	94	06	1.8
0–8.0	57	80	90	94	06	1.8
	Meridional component of the wind velocity, m/s					
0–0.2	85	95	96	99	01	1.0
0–0.4	77	93	95	99	01	1.1
0–0.8	67	86	93	98	02	1.4
0–1.2	60	85	92	95	05	1.6
0–1.6	56	85	91	94	06	1.7
0–2.0	55	84	90	94	06	1.8
0–2.4	55	82	89	93	07	1.8
0–3.0	55	81	89	93	07	1.9
0–4.0	52	81	98	93	07	1.9
0–5.0	50	78	88	93	07	2.0
0–6.0	47	78	87	93	07	2.0
0–8.0	46	76	86	93	07	2.0

The last conclusion is especially important for practice as the wind is the most critical parameter in numerical estimation of the pollution clouds dispersal and in talking the tasks of the military geophysics.

3.2. Results on the quality of algorithm of objective analysis of mesometeorological fields obtained by statistical assessment

Consider now statistically assessed quality of the algorithm of objective analysis of the mesoscale meteorological fields we have used in the AMS. The results of such an analysis are normally used in local forecast, which is being done based on the known hydrothermodynamics equations of the mesoscale processes.[7]

It should be noted here that the main peculiarities of the algorithm of objective analysis of the mesometeorological fields is, first, that it uses the same prognostic model, as the spatial extrapolation does. The model allows for the correlation properties of meteorological fields. Second, the algorithm enables one to estimate the field of a meteorological quantity not at arbitrary points of space or along a trajectory, but at the nodes of a regular grid.

As an example Table 2 gives the values of the standard error δ_ξ and the probability P that the errors of objective analysis are below or exceed preset values. The analysis has been performed of the fields of geopotential, temperature, zonal and meridional components of the wind velocity in winter.

Table 2. Standard error δ_ξ and the probability *P* of errors in the objective analysis of mesometeorological fields carried out using the AMS for the control station in Sukhinichi. Winter

Layer, hPa	$P \cdot 10^2$					δ_ξ
	$\Delta_i \le \pm 1$	$\Delta_i \le \pm 2$	$\Delta_i \le \pm 3$	$\Delta_i \le \pm 4$	$\Delta_i > \pm 4$	
	Geopotential, dkm					
925	62	83	93	96	04	1.5
850	56	78	93	96	04	1.6
700	55	75	90	95	05	1.8
500	55	74	90	94	06	1.9
400	55	73	86	93	07	1.9
300	52	70	82	88	12	2.1
	Temperature, °C					
925	62	86	93	98	02	1.4
850	64	87	94	97	03	1.5
700	68	86	94	97	03	1.4
500	68	87	94	98	02	1.3
400	69	88	94	99	01	1.2
300	70	88	94	100	00	1.2
	Zonal component of the wind velocity, m/s					
925	52	72	85	93	07	2.1
850	50	68	80	90	10	2.3
700	50	65	77	90	10	2.3
500	50	63	75	85	15	2.7
400	52	63	75	82	18	2.8
300	53	63	76	81	19	2.9
	Meridional component of the wind velocity, m/s					
925	56	71	85	92	08	2.0
850	50	66	82	91	09	2.1
700	49	66	76	87	13	2.5
500	51	67	76	86	14	2.6
400	53	66	76	86	14	2.6
300	54	66	77	88	12	2.5

Analysis of the data presented in Table 2 shows that:

– the algorithm of objective analysis gives practically quite reliable results, because independent of the season and the atmospheric layer the standard errors of such an analysis are about 1.5 to 2.1 dkm (geopotential), 1.2 to 1.5°C (temperature), and 2.0 to 2.9 m/s (orthogonal components of the wind velocity);

– the objective analysis carried out using the AMS gives the best-quality results in interpolating the mesoscale fields of temperature. Thus, the probability of errors less than ± 1°C is about 0.62 to 0.70 independent of season and atmospheric layer, while for $\Delta_i \le 2$°C it reaches even the values from 0.86 to 0.88.

3.3. Results on the quality of algorithm of forecasting the atmospheric parameters obtained by statistical assessment

Finally, consider the statistically assessed quality of the algorithm, which we have used in the AMS for predicting in time the atmospheric parameters. This algorithm employs the apparatus of Kalman filtering and dynamic-stochastic model, which is based on a system of linear stochastic equations describing the evolution of a random process.

For this purpose, let us make use of the data given in Table 3. This table presents, as an example, standard δ_ξ and relative θ (%) errors in the forecast (lead time τ = 12 h) of geopotential, temperature, zonal and meridional components of the wind velocity made for a winter period using data from Sukhinichi station.

Table 3. Standard δ_ξ and relative θ (%) errors in the forecast (lead time τ = 12 h) of the atmospheric parameters made using the AMS for Sukhinichi station. Winter

Level, hPa	Geopotential, dkm		Temperature, °C		Zonal wind, m/s		Meridional wind, m/s	
	δ_H	θ	δ_T	θ	δ_{Vx}	θ	δ_{Vy}	θ
925	2.8	32	1.9	36	2.8	51	3.5	57
850	2.9	32	1.9	34	3.2	54	4.0	54
700	3.0	28	1.9	34	3.7	54	4.5	55
500	3.5	25	1.9	34	4.8	54	6.9	52
400	4.3	25	1.8	37	6.0	54	7.9	50
300	4.8	25	1.5	38	6.9	53	8.5	50

Analysis of the data presented in Table 3 shows that:

– the forecast algorithm used in the AMS gives most accurate results in forecasting the geopotential and temperature when the relative errors in such a forecast vary within the limits from 25 to 32 and from 34 to 38%, respectively;

– the forecast algorithm gives the least accurate data if the extrapolation in time is being done of the wind velocity components, since the relative uncertainties of such a forecast are about 50 to 57% independent of the atmospheric level and the component forecasted.

It should be noted here that in the case of very-short-term forecast (i.e., for the lead time $\tau \leq 6$ h) the algorithms proposed should yield much better extrapolation results. This is confirmed, in particular, by the forecast made for the near-ground temperature measured with an automated AMK-3 meteorological complex in the suburbs of Tomsk. As follows from the obtained results the values of the rms errors of the very-short-term forecast of the near-ground temperature made for the lead time of 3 and 6 hours are 1.0 and 1.3°C. The probability values that the errors are below ±1°C were 0.81 and 0.70, respectively.

Conclusion

The above analysis of the quality of the forecast algorithms used in the automated meteorological system has shown that the algorithms (especially the algorithms of spatial extrapolation and objective analysis) are quite reliable and, therefore, the AMS developed can successfully be used as an information support system in ecology and military geophysics. However, it is worth noting that the AMS effectiveness could be essentially improved if the following revisions of the system are made:

1) an updated algorithm of spatial extrapolation of the mesometeorological fields proposed in Ref. 8 should be used, which is based on Kalman filtering and four-dimensional dynamic-stochastic model. This algorithm yield about 1.2 to 1.5 times more accurate data as compared with those obtained using the AMS algorithms used;

2) a new algorithm of very-short-term forecast of the atmospheric parameters has to be developed based on the use of Kalman filtering apparatus and mixed dynamic-stochastic model capable of allowing for the variations of the meteorological fields in space (height) and time;

3) the system has to use, along with the data of radiosondes, the information from meteorological stations, mobile sounding systems, including data of lidar, radiometric and acoustic sounding of the atmosphere;

4) the prognostic algorithms are to be adapted to fast changes of the state of the atmosphere (e.g., during the front passages), as well as to varying configuration of the local networks of stations (especially of the mobile ones) and their number;

5) some elements of the GIS technology should be used in mapping the isolines obtained from objective analysis of mesometeorological fields of a given geographical region.

6) use of an automated search and retrieval of the information needed from the general flow of data received through communication lines as well as automated distribution of the prognostic information among the end users.

References

1. V.S. Komarov, A.Ya. Bogushevich, A.V. Kreminskii, Yu.B. Popov, and A.I. Popova Atmos. Oceanic Opt. **18**, No. 8, 626–634 (2005).
2. L.S. Gandin and R.L. Kagan, *Statistical Methods of Interpreting the Meteorological Data* (Gidrometeoizdat, Moscow, 1976), 359 pp.
3. F.F. Bryukhan,' *Methods of Climatic Processing and Analysis of the Aerological Information* (Gidrometeoizdat, Moscow, 1983), 112 pp.
4. S.P. Khromov and L.I. Mamontova, *Meteorological Vocabulary* (Gidrometeoizdat, Leningrad, 1974), 568 pp.
5. S.P. Khromov and M.A. Petrosyants, *Meteorology and Climatology* (MSU, Kolos S Publishing House, Moscow, 2004), 582 pp.
6. V.D. Reshetov, Tr. Tsentr. Aerol. Obs., Issue. 133, 55–64 (1978).
7. P.N. Belov, E.P. Borisenkov, and B.D. Panin, *Numerical Methods of the Weather Forecast* (Gidrometeoizdat, Leningrad, 1989), 376 pp.
8. V.S. Komarov, A.V. Lavrinenko, N.Ya. Lomakina, Yu.B. Popov, A.I. Popova, and S.N. Il'in, Atmos. Oceanic Opt. **17**, No. 8, 584–590 (2004).