Numerical retrieval of temperature and wind profiles in the boundary atmospheric layer based on the Kalman filter algorithm and 2D dynamical-stochastic model. Part 2. Results of investigation

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Received December 10, 2007

Results of experimental investigation of the quality of numerical retrieval of air temperature and wind profiles in the boundary atmospheric layer, using the 2D dynamical-stochastic model and the Kalman filter method, are discussed.

A new methodical approach[1] was proposed to solve the problem of numerical retrieval of the vertical profiles of some meteorological parameter in the atmospheric boundary layer (ABL). The approach is based on application of the Kalman filter algorithm and the 2D dynamical-stochastic model, which simultaneously takes into account both the peculiarities of the vertical structure of the field of the meteorological parameter and the dynamics of its temporal variations.

The purpose of this paper is consideration of the results of numerical estimation of the quality and efficiency of the proposed[1] dynamical-stochastic approach by the example of the retrieval (from experimental data) of vertical profiles of the temperature and orthogonal components of the wind velocity up to the height of 1.6 km.

To study the quality of the Kalman filter algorithm using 2D dynamical-stochastic model,[1] the data array of balloon observations recorded two times a day (00 and 12 GMT) in January and July, 2004 at two aerological stations: Moscow (55°45′N, 37°57′ E) and Novosibirsk (54°58′N, 82°57′E) was considered. The stations are situated in the regions with different physical-geographic conditions. All aerological data used for formation of the initial data array were preliminary interpolated (using the method of linear interpolation) from standard isobaric surfaces: 1000, 975, 850, and 700 hPa and the levels of peculiar points (including the ground level) to given geometric heights: 0, 100, 200, 300, 400, 600, 800, 1000, and 1600 m. Besides, not wind velocity and direction were taken for statistical estimation of the quality of retrieval of the wind profile, but its zonal and meridional components, the behavior of which is more stable in time.

To realize the Kalman filter algorithm,[1] some initial conditions were set at the time moment $k = 0$ (initialization moment), i.e., in the absence of *a priori* data, namely:

– the initial vector of estimates $x_0^a = 0$ (i.e., the model parameters $d_{j,m} = 0$) that is caused by the absence of useful data on the behavior of these parameters;

– initial correlation matrix of the observed noises $\mathbf{R}_k = \mathbf{R}_0$, the elements of which at the principal diagonal r_{ii} (under the condition that the noises $\varepsilon_h(k)$ are uncorrelated) are taken equal to 0.7°C for temperature and 1.0 m/s for orthogonal components of wind velocity, based on errors in balloon observations[2];

– initial correlation matrix of the state noises $\mathbf{Q}_k = \mathbf{Q}_0$, the elements of which on the principal diagonal q_{ii} (under the condition that the noises $\boldsymbol{w}(k)$ are uncorrelated as well) are set equal to 1, based on the preliminary analysis of the behavior of the vector of state composed from unknown dimensionless parameters of the model.

Besides, according to Ref. 3, the covariance matrix of estimating errors $\mathbf{P}_k^a$, should be used in calculations of the weight coefficients $\mathbf{K}_k$ in the linear Kalman filter, which should be set at the moment of initialization of this filter. In practice, $\mathbf{P}_k^a = \mathbf{P}_0^a$, the matrix $\mathbf{P}_0^a$ has a diagonal form, the elements of which at the principal diagonal should lie in the limits $P_{ij} = 1, ..., 100$ (in our case, as preliminary analysis has shown, $P_{ij} = 10$), all other equal to zero.

As for estimation of the quality of the proposed algorithm by the example of temperature T, °C, zonal U, m/s, and meridional V, m/s components of wind velocity, it was carried out using the standard (root-mean-square) error in numerical retrieval, determined by the formula

$$\delta_\xi = \left| \frac{1}{N} \sum_{k=1}^{N} \left(\xi_{0,k}^a - \xi_{0,k}^0 \right)^2 \right|^{1/2}, \quad (1)$$

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where $\xi^a_{0,k}$ and $\xi^0_{0,k}$, respectively, are the retrieved and actual values of the meteorological parameter at the point of retrieval (x_0, y_0) at the time moment k; N is the number of considered realizations, as well as using the probability P of the errors in such retrieval $\Delta_k = \xi^a_k - \xi^0_k$, which are less or greater than a certain given value (for temperature, less than ±1, ..., ±4°C and greater than ±4°C, and for orthogonal components of wind velocity less than ±1, ..., ±4 m/s and greater than ±4 m/s).

Let us now consider the results of the study. First, like in Ref. 4, compare time behaviors of actual measurements, retrieved values, and current errors.

Temporal behaviors (during the period from 01.14.04 00:00 GMT to 01.18.04 12:00 GMT and from 01.11.04 00:00 GMT to 01.15.04 12:00 GMT, respectively) of the observed values ξ^0_k, retrieved values ξ^a_k, and current errors Δ_k in retrieving temperature, zonal and meridional components of wind velocity at three typical height levels: 100, 600, and 1600 m are shown in Figs. 1 and 2 for two stations (Moscow and Novosibirsk).

Analysis of Figs. 1 and 2 shows that observed and retrieved values of temperature, zonal and meridional components of wind velocity are in sufficiently good agreement. The observed and retrieved values of temperature are especially close to each other, for which the retrieval errors, in general, do not exceed 0.5°C.

However, to finally confirm the high quality of the proposed dynamical-stochastic algorithm, it is expedient to statistically estimate its accuracy using the standard (root-mean-square) errors δ_ξ and the probabilities P of the errors.

The data on such estimate for stations Moscow and Novosibirsk are presented in Tables 1 and 2.

Joint analysis of Tables 1 and 2 shows that the use of the Kalman filter algorithm with 2D dynamical-stochastic model for numerical retrieval of the vertical profiles of temperature and orthogonal components of wind velocity really provides the results acceptable in practice for the total boundary layer independently of the considered station. For example, the standard errors in such retrieval do not exceed 0.9°C in winter and 0.6°C in summer (for temperature) and, respectively, 2.5 and 1.4 m/s for zonal and meridional components of wind velocity.

Besides, the values of probability of small errors in the retrieving (less than ± 1°C for temperature and less than ± 1 m/s for orthogonal components of wind velocity) evidence quite high quality of the algorithm. However, the probability of the errors less than ± 1°C in retrieving the temperature in the boundary layer (independently of the considered station or season) is within 0.80 – 1.00, while the probability of the errors less than ± 1 m/s in retrieving the components of wind velocity varies in close limits (0.64 – 1.00) only in summer (similar values in winter are observed mainly in the layer up to 400 m).

Table 1. Standard errors δ_ξ of probability P ($\cdot 10^2$) of the errors in retrieving the vertical profiles of temperature and wind velocity components relative to a given value for st. Moscow

Height, m	Winter						Summer					
	P					δ_ξ	*P*					δ_ξ
	≤±1	≤±2	≤±3	≤±4	>±4		≤±1	≤±2	≤±3	≤±4	>±4	
Temperature, °C												
100	100	100	100	100	0	0.2	100	100	100	100	0	0.2
200	96	100	100	100	0	0.4	100	100	100	100	0	0.2
300	95	100	100	100	0	0.5	100	100	100	100	0	0.3
400	82	100	100	100	0	0.7	98	100	100	100	0	0.3
600	81	97	100	100	0	0.8	97	100	100	100	0	0.4
800	81	96	100	100	0	0.8	97	100	100	100	0	0.4
1000	80	96	100	100	0	0.9	95	100	100	100	0	0.4
1200	80	96	100	100	0	0.9	94	100	100	100	0	0.5
1600	80	95	100	100	0	0.9	90	100	100	100	0	0.6
Zonal component of wind velocity, m/s												
100	98	100	100	100	0	0.3	98	100	100	100	0	0.3
200	98	99	100	100	0	0.6	98	100	100	100	0	0.3
300	76	95	97	98	2	1.2	97	99	100	100	0	0.5
400	62	90	95	96	3	1.7	95	97	100	100	0	0.7
600	53	76	93	95	5	1.9	95	97	100	100	0	0.7
800	45	66	88	91	9	2.2	94	97	100	100	0	0.7
1000	44	64	86	90	10	2.3	94	97	100	100	0	0.7
1200	40	62	84	90	10	2.4	89	97	100	100	0	0.8
1600	38	60	83	88	12	2.5	83	92	98	100	0	1.0
Meridional component of wind velocity, m/s												
100	100	100	100	100	0	0.3	100	100	100	100	0	0.1
200	90	98	100	100	0	0.6	100	100	100	100	0	0.3
300	76	96	98	100	0	0.9	95	100	100	100	0	0.4
400	67	90	95	98	2	1.3	94	100	100	100	0	0.5
600	52	70	86	98	2	1.8	86	100	100	100	0	0.7
800	40	68	84	95	5	2.0	84	100	100	100	0	0.8
1000	39	66	84	93	7	2.1	83	100	100	100	0	0.8
1200	37	64	83	92	8	2.2	75	98	100	100	0	0.9
1600	35	60	83	91	9	2.3	70	94	100	100	0	1.0

However, the question whether the proposed algorithm is more effective than the modified method for clustering the arguments,[5] remains open.

To clarify this, use Table 3, presenting the values of standard δ_ξ and relative $\theta_\xi = \delta_\xi/\sigma_\xi$ (here σ_ξ is the root-mean-square deviation) errors in retrieving the values of temperature $\langle T\rangle_{h_0,h}$ and orthogonal components of wind velocity $\langle U\rangle_{h_0,h}$ and $\langle V\rangle_{h_0,h}$ calculated by the data obtained at station Novosibirsk using two methods: MMCA and Kalman filter with 2D dynamical-stochastic model.

The question can appear here, why not observations of the considered meteorological parameters are taken as the atmospheric parameters to be retrieved, but their values averaged over the layer? This is caused by the fact that, when comparing the efficiency of two alternative methods, we used, analogously to Ref. 6, the results of numerical estimation of the quality of retrieval of $\langle T\rangle_{h_0,h}$, $\langle U\rangle_{h_0,h}$, and $\langle V\rangle_{h_0,h}$, widely used for calculations of the spatial distribution of a cloud of pollution, when the mean data for some atmospheric layer have been taken instead of level observations of temperature and wind.[7]

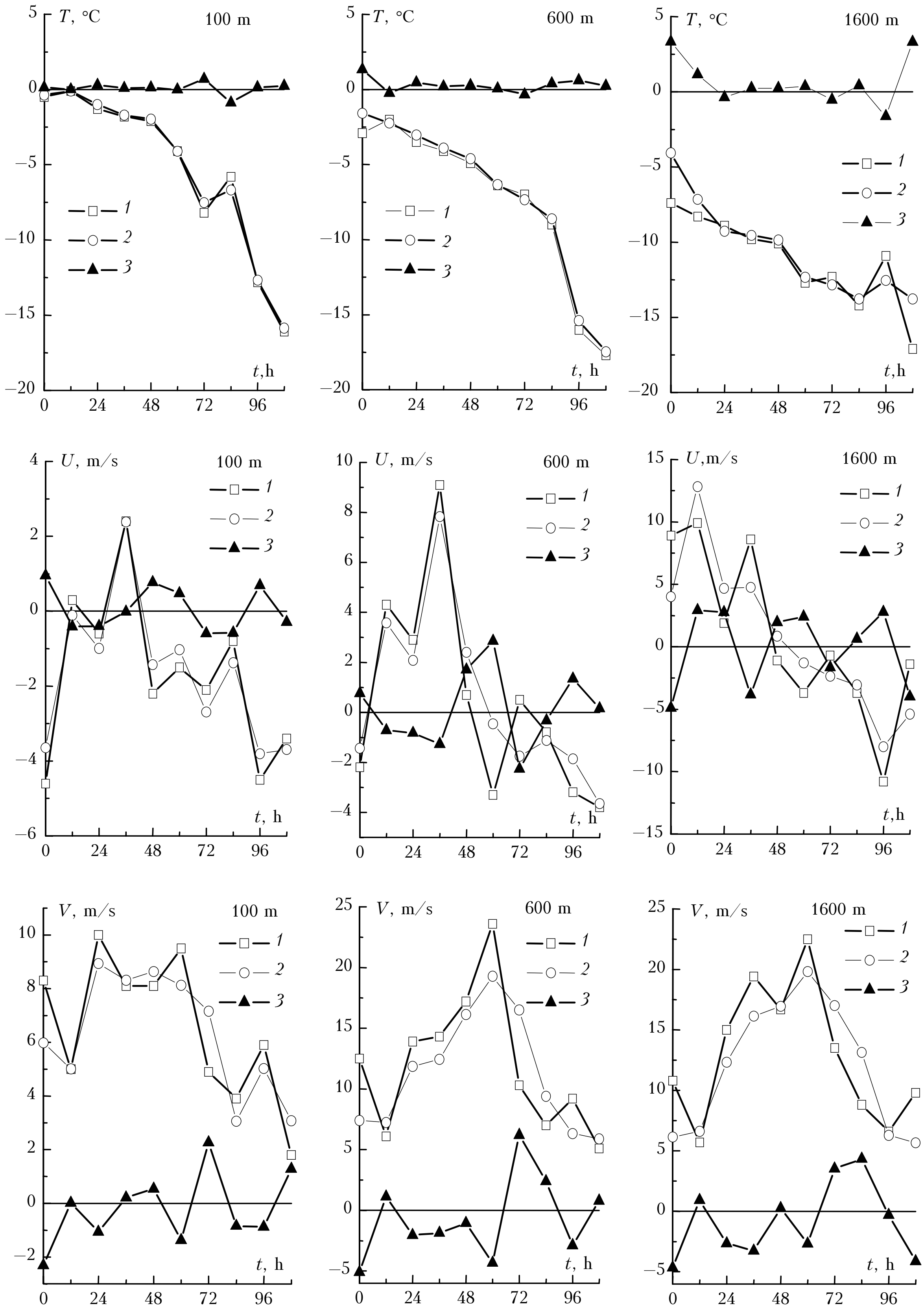

Fig. 1. Temporal behavior of observed measurements (*1*), retrieved values (*2*), and current errors (*3*) in retrieving temperature, zonal and meridional components of wind velocity at individual levels, obtained at the test station Moscow.

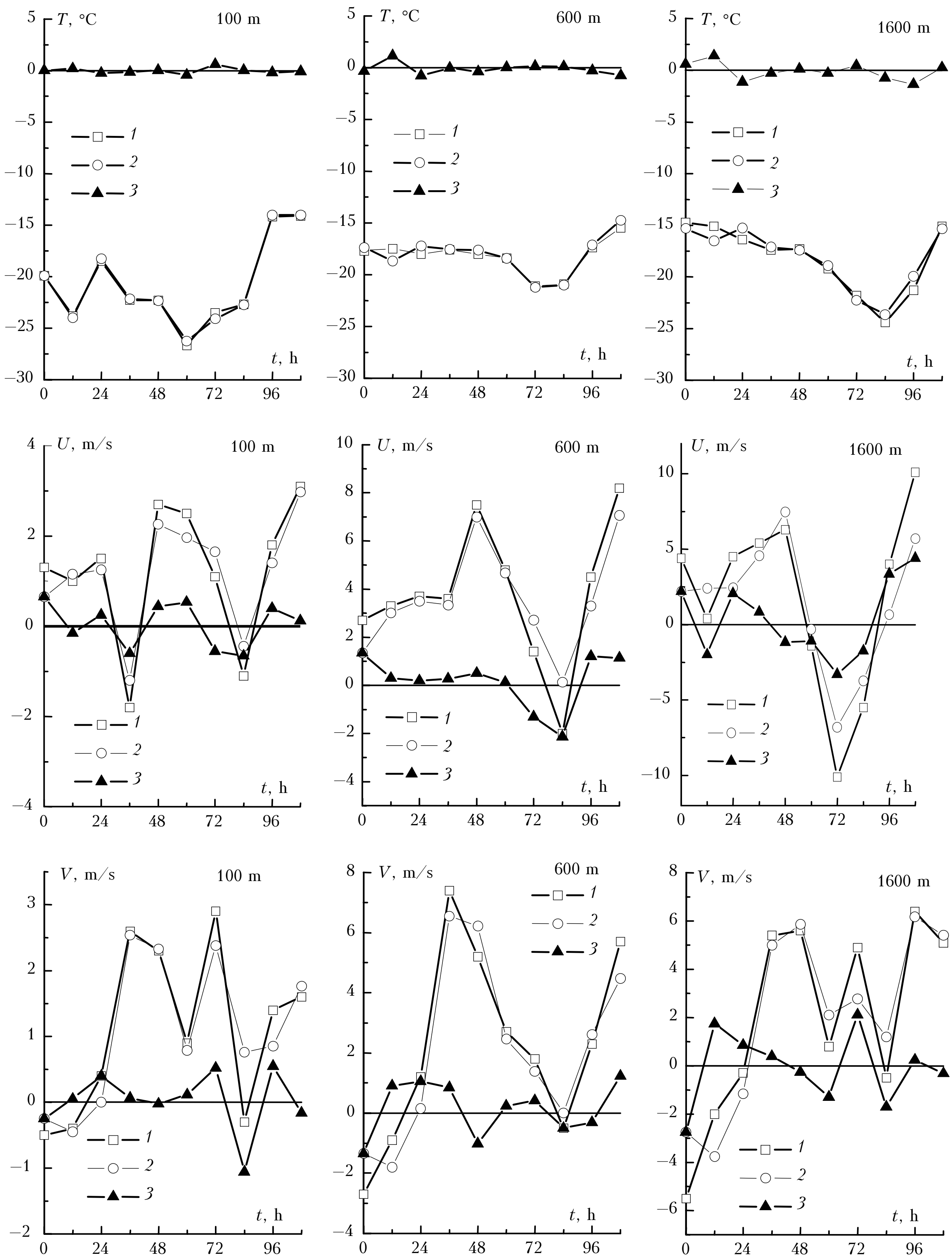

Fig. 2. Temporal behavior of observed measurements (*1*), retrieved values (*2*), and current errors (*3*) in retrieving temperature, zonal and meridional components of wind velocity at individual levels, obtained at the test station Novosibirsk.

Table 2. Standard errors δ_ξ of probability P ($\cdot\ 10^2$) of the errors in retrieving meteorological parameters for st. Novosibirsk

Layer, m	Winter						Summer					
	P					δ_ξ	P					δ_ξ
	≤±1	≤±2	≤±3	≤±4	>±4		≤±1	≤±2	≤±3	≤±4	>±4	
Temperature, °C												
0–100	100	100	100	100	0	0.3	100	100	100	100	0	0.2
0–200	92	100	100	100	0	0.6	97	100	100	100	0	0.3
0–300	92	100	100	100	0	0.6	93	100	100	100	0	0.5
0–400	92	100	100	100	0	0.6	93	100	100	100	0	0.5
0–600	92	100	100	100	0	0.6	93	100	100	100	0	0.5
0–800	92	100	100	100	0	0.6	93	100	100	100	0	0.5
0–1000	92	100	100	100	0	0.6	93	100	100	100	0	0.5
0–1200	92	100	100	100	0	0.6	93	100	100	100	0	0.5
0–1600	92	100	100	100	0	0.6	93	100	100	100	0	0.5
Zonal component of wind velocity, m/s												
0–100	98	100	100	100	0	0.4	85	100	100	100	0	0.7
0–200	83	100	100	100	0	0.7	75	96	100	100	0	0.8
0–300	75	98	100	100	0	0.9	68	96	100	100	0	1.0
0–400	65	93	95	100	0	1.1	68	93	100	100	0	1.0
0–600	60	88	95	98	2	1.5	68	93	100	100	0	1.0
0–800	58	88	95	98	2	1.6	68	93	100	100	0	1.0
0–1000	58	85	95	98	2	1.8	67	93	100	100	0	1.0
0–1200	58	85	95	98	2	1.8	66	90	100	100	0	1.1
0–1600	58	85	90	98	2	1.9	65	90	100	100	0	1.2
Meridional component of wind velocity, m/s												
0–100	90	98	100	100	0	0.6	91	97	100	100	0	0.6
0–200	78	98	100	100	0	0.9	91	97	100	100	0	0.6
0–300	70	98	100	100	0	0.9	84	97	100	100	0	0.8
0–400	68	98	100	100	0	0.9	77	97	100	100	0	0.9
0–600	68	98	100	100	0	0.9	70	97	100	100	0	1.0
0–800	68	98	100	100	0	0.9	69	94	100	100	0	1.1
0–1000	68	97	99	100	0	1.0	67	94	100	100	0	1.3
0–1200	60	95	98	100	0	1.1	66	94	100	100	0	1.3
0–1600	55	88	98	100	0	1.3	64	88	97	100	0	1.4

Analysis of the data in Table 3 shows that the proposed algorithm based on application of the Kalman filter and 2D dynamical-stochastic model provides (in comparison with the MMCA algorithm) essentially better quality of the results of numerical retrieval of layer-average values of temperature, zonal and meridional components of wind velocity. Actually, the use of the algorithm of Kalman makes it possible to improve the quality of retrieval, independently of season and the atmospheric layer, by 2.8–4.7 times for $\langle T\rangle_{h_0,h}$ and by 2.0–2.8 times for $\langle U\rangle_{h_0,h}$ and $\langle V\rangle_{h_0,h}$. Moreover, the relative error θ_ξ in such retrieval of layer-average values is 4–8% for temperature and 12–25% for layer-average values of the velocity of zonal and meridional wind (when using the MMCA algorithm the values θ_ξ vary within the limits 13–33 and 24–57%, respectively). All this evidences a high accuracy and efficiency of numerical retrieval of the parameters $\langle T\rangle_{h_0,h}$, $\langle U\rangle_{h_0,h}$, and $\langle V\rangle_{h_0,h}$ in the case when the Kalman filter with 2D dynamical-stochastic model has been taken as the algorithm for vertical extrapolation.

Table 3. Standard δ_ξ and relative θ_ξ errors of probability P of the errors in retrieving the vertical profiles of temperature, zonal and meridional components of wind velocity relative to a given value carried out using the algorithm MMCA (1) and Kalman filter with 2D dynamical-stochastic model (2) for station Novosibirsk

Layer, m	Winter				Summer			
	δ_ξ		θ_ξ		δ_ξ		θ_ξ	
	1	2	1	2	1	2	1	2
Temperature, °C								
0–200	0.9	0.3	13	04	0.8	0.2	16	04
0–400	1.1	0.4	17	06	1.0	0.3	20	06
0–800	1.4	0.4	22	06	1.2	0.3	25	06
0–1200	1.6	0.4	26	06	1.4	0.3	30	06
0–1600	1.8	0.4	30	07	1.5	0.4	33	08
Zonal component of wind velocity, m/s								
0–200	1.1	0.4	35	13	1.1	0.4	39	14
0–400	1.4	0.6	36	15	1.3	0.6	43	20
0–800	1.8	0.8	40	18	1.6	0.7	48	21
0–1200	2.1	1.0	44	21	1.8	0.7	53	21
0–1600	2.3	1.1	45	22	2.0	0.9	57	25
Meridional component of wind velocity, m/s								
0–200	0.8	0.4	27	13	0.6	0.3	24	12
0–400	1.2	0.6	35	18	0.9	0.5	32	18
0–800	1.5	0.7	42	19	1.2	0.6	39	19
0–1200	1.8	0.7	49	19	1.6	0.7	50	22
0–1600	2.0	0.8	50	20	1.8	0.8	53	24

It should be said in conclusion that the proposed algorithm provides for higher results in retrieving (both the considered meteorological parameters and especially their layer-average values) if to use not the data of balloon sensing, conducted twice a day, but, for example, the data of lidar remote sensing, which have a high temporal resolution.

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