Peculiarities in the vertical statistical structure of temperature, humidity, and wind fields in the atmospheric boundary layer of Western Siberia. Part 1. Background characteristics and variability

V.S. Komarov and N.Ya. Lomakina

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

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The results of the complex physical-statistical analysis of vertical structure of temperature, humidity, and wind fields in the atmospheric boundary layer of Western Siberia, made by data of long-term observations at eight aerological stations, are considered. Some methodical aspects of initial data preparation and the peculiarities of the vertical distribution of background (mean climatic) characteristics and variances of temperature, humidity, and wind up to a height of 1600 m depending on the season and geographic position of the station are described.

Introduction

The solution of numerous problems connected with study and modeling mesoclimates, the development and application of systems of laser remote sensing of atmospheric parameters, the evaluation of conditions of propagation in air of electromagnetic (including optical) radiation, etc., calls for further widening of our knowledge of the vertical statistical structure of fields of temperature, humidity, and wind in the atmospheric boundary layer (ABL) over different regions of the Earth, especially over such poorly explored (climatically) region as Western Siberia.

For a long time in the meteorological literature (see, for example, Ref. 1) a considerable attention was given to the statistical structure of meteorological fields in the free atmosphere. The investigations were carried out based on data of only standard isobaric levels without attracting the data of singular points (points in the vertical profiles with large vertical derivative of one of meteorological parameters),[2] that excluded a possibility of studying such a structure in the atmospheric boundary layer. Only in Ref. 3 the data of standard isobaric levels and singular points, along with the analysis of vertical statistical structure of meteorological fields in the free atmosphere over the northern hemisphere are used for studying the same structure in the atmospheric boundary layer including the territory of Western Siberia. However, in this investigation the data of only three stations were used: Salekhard, Sverdlovsk and Novosibirsk, taken at the height resolution about 250 m; besides, the wind fields were not considered. All this does not result in a proper description of the temperature and humidity vertical distribution in the atmospheric boundary layer over the entire territory of Western Siberia; especially, in the lower 600 m layer, where this distribution is formed mainly under dynamic and thermal effect of the underlying surface.

As for the other papers on the same topic, they present data rather tentative, because they are obtained either from long-term radiozonde observations of temperature and wind at one station (Novosibirsk)[4] or from limited experimental (lidar[5] or sodar[6]) measurements of wind characteristics in the vicinity of Tomsk. As a result, in Ref. 5, only the profiles of altitude distribution of mean values and dispersions of wind parameters are considered; while in Ref. 6 only their inter-level correlations are presented, estimated only for the lower 300-m atmospheric layer.

All this underlines the importance of investigating the characteristics of the vertical structure of the temperature, humidity, and wind in the atmospheric boundary layer over the territory of Western Siberia. This is the goal of our paper.

1. Characteristic of the initial material

The basic initial materials for our investigation were the five-year (2001–2005) and two-time (at 00 and 12 hr by GMT) radiosonde observations at eight aerological stations: Salekhard (66°32′N, 66°40′E), Turukhansk (65°47′N, 87°56′E), Khanty-Mansiisk (61°01′N, 69°02′E), Aleksandrovskoye (60°26′N, 77°52′E), Verkhnee Dubrovo (56°44′N, 61°40′E), Omsk (54°56′N, 73°24′E), Novosibirsk (54°58′N, 82°57′E) and Emel'yanovo (56°11′N, 92°37′E).

Since we use the five year period of averaging, there arises a question about the representativeness of the above period and applicability of the obtained statistical characteristics as certain climatic standards. To answer this question, we have estimated, using Novosibirsk region as an example, the significance of the divergence of means $\bar{\xi}_1$ and $\bar{\xi}_2$ and variances σ_1^2

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and σ_2^2 calculated by two independent samples N_1 and N_2 with the use of the Student distribution t_s, (for comparison of means) and the Fisher effect T_H (for comparison of variances).[7]

Table presents the results of the comparison of means and variances for the temperature and orthogonal components of wind velocity by criteria t_s and T_H calculated for Novosibirsk based on the sample N_1 (1961–1970) and the sample N_2 (2001–2005).

Note that the means and variances, obtained using the sample N_1, were taken from Ref. 8 (for the temperature) and supplemented by the latest calculations for the wind; the samples N_1 and N_2 included 230 and 138 observations for January and 260 and 152 for July, respectively.

The analysis of results of comparison of means and variances of temperature, zonal and meridional wind, calculated by N_1 and N_2 for the ground level and isobaric surfaces of 925 and 850 hPa, located in the atmospheric boundary layer, has shown that the criterion t_s in all cases, i.e., regardless of the meteorological value, month, and the atmospheric level, is less than its critical value $t_s(P, k) = 1.96$, determined with the probability $P = 0.95$ and the number of degrees of freedom

$$k = N_1 + N_2 - 2 = 230 + 138 - 2 = 366 \text{ for January}$$

and

$$k = N_1 + N_2 - 2 = 260 + 152 - 2 = 410$$

for July; and the criterion T_H is less than $F_{1-P}(N_1, N_2)$, which is equal, respectively, to 1.31 and 1.28 at the level of significance $S = 1 - P = 0.05$ and at the given values of N_1 and N_2.

Consequently, the difference between both mean values and variances of taken meteorological parameters, calculated over two independent samples for three levels, is unessential and random. Therefore, the sample used by us is fully representative, and the statistical characteristics, obtained on its basis, can be considered as climatic standards.

Now we dwell on some peculiarities of the formation of initial statistical sets used for calculating the characteristics of the vertical structure of meteorological fields; as these characteristics, we used: means $\bar{\xi}(h_e)$, rams deviations $\sigma_\xi(h_i)$, and autocorrelation (normalized) functions $\mu_{\xi\xi}(h_i, h_e)$.

To form these sets we used the following procedures:

– first, all aerological data were preinterpolated (using the linear interpolation method) from standard isobaric surfaces: 1000 (the ground level), 925, 850 and 700 hPa and levels of singular points to the given geometric heights: 0, 100, 200, 300, 400, 600, 800, 1000, 1200, and 1600 m;

– second, aerological measurements, obtained for different stations, were synchronized in time; this resulted in 138 simultaneous measurements for each station for January and 152 for July, that has made it possible to obtain samples, homogeneous in height and space, as well as, in the first approximation, random and independent;

– third, when forming initial samples, a many-year month was chosen as a period of averaging, which excluded nonstationarity in the taken meteorological series, characteristic for averaging over a year or a season and distorting the obtained statistics;

– fourth, when forming data file of humidity, the values of water vapor fraction of total mass (q, ‰) were taken; the fraction cannot be measured, therefore it was calculated by the formula[2]

$$q = 622 E_w(T_d)/p, \tag{1}$$

where $T_d = (273.16 + t_d)$ is the dew point (K) (here t_d is the same dew point, °C); $E_w(T_d)$ is the actual partial pressure of water vapor in hPa, estimated by the relation to water, and p is the atmospheric pressure (hPa); in this case the dependence of the value $E_w(T_d)$ on the dew point T_d can be represented according to the Technical regulation of IMS[9] by an empirical formula

Table. Mean values of temperature (t, °C), velocity of zonal (U, m/s), and meridional (V, m/s) winds and their rms deviations (σ), calculated for the Novosibirsk station over the periods from 1961 to 1970 and from 2001 to 2005, and values of criteria of significance t_s and T_H

Level, hPa	January						July					
	1961–1970		2001–2005		t_s	T_H	1961–1970		2001–2005		t_s	T_H
	$\bar{\xi}_1$	σ_1	$\bar{\xi}_2$	σ_2			$\bar{\xi}_1$	σ_1	$\bar{\xi}_2$	σ_2		
Temperature												
Earth	−17.1	8.5	−16.5	7.7	0.70	1.22	18.8	4.9	18.4	5.5	0.74	1.26
925	−13.0	6.3	−11.8	5.7	1.87	1.22	15.0	4.2	15.6	4.3	1.37	1.05
850	−13.9	5.5	−12.8	5.3	1.89	1.08	9.8	3.8	10.2	4.0	0.99	1.11
Zonal wind velocity												
Earth	0.5	2.2	0.9	2.1	1.74	1.10	0.0	1.6	0.1	1.8	0.57	1.26
925	5.4	7.4	6.3	7.1	1.16	1.09	0.4	4.4	0.6	4.6	0.43	1.09
850	6.5	8.4	7.3	8.1	0.90	1.08	1.0	4.8	1.1	4.9	0.20	1.04
Meridional wind velocity												
Earth	1.1	1.6	0.8	1.8	1.63	1.26	−0.1	1.5	−0.6	1.6	0.61	1.14
925	2.5	6.0	1.4	5.5	1.76	1.19	−0.2	4.5	−0.7	4.7	1.14	1.09
850	1.4	6.3	0.3	5.7	1.72	1.22	−0.1	4.8	−0.4	5.0	0.59	1.08

$$\log E_{\rm w}(T_{\rm d}) = 10.79574\left(1 - \frac{273.16}{T_{\rm d}}\right) -$$

$$- 5.028\log\left(\frac{T_{\rm d}}{273.16}\right) + 1.50475\cdot 10^{-4}\left[1 - 10^{-8.2969\left(\frac{T_{\rm d}}{273.16}-1\right)}\right] +$$

$$+ 0.42873\cdot 10^{-3}\left[10^{4.76955\left(1-\frac{273.16}{T_{\rm d}}\right)} - 1\right] + 0.78614; \quad (2)$$

– and, finally, fifth, after the formation of statistical sets, each term of the considered set was tested climatically through the expression[3]:

$$\left|\xi_i - \bar{\xi}\right| \geq 3\sigma_\xi. \quad (3)$$

(Here ξ_i and $\bar{\xi}$ denote the controlled value of the meteorological parameter and its climatic standard at some atmospheric level, respectively, and σ is the rms deviation obtained for the same level). As a result, no more than 1–3% of measurements were rejected. Since the vertical profiles of $\xi_i(h)$, having incorrect values at individual levels, were excluded from further consideration and the statistical sets homogeneous in height were obtained, which served a basis for calculation of all statistics.

2. Some peculiarities of vertical structure of mean fields of temperature, humidity, and wind in the atmospheric boundary layer

It is known that the pattern of the vertical structure of any meteorological field becomes most clear from the analysis of the field background (mean) characteristics inherent to this field. This Section describes some results of such analysis carried out for the Western Siberia region.

Note that the results of statistical analysis of background characteristics will be described separately for the complex temperature–humidity (a close correlation exists between them[3]) and the wind vector parameters presented by its zonal and meridional components. The use of these components depends upon the fact that the analysis of wind velocity and direction, measured by the radiosonde, is impossible because the mean value of the wind direction, generally speaking, can be nonexistent.[1] For simplicity, we will use the term "the velocity of zonal or meridional wind." In this case positive values of zonal wind velocity correspond to the west transfer, and negative values correspond to the east transfer. Similarly, positive values of the meridional wind velocity correspond to the south transfer, and the negative values correspond to the north transfer.

It follows from Fig. 1, where the vertical distribution of mean temperature and humidity is shown for stations of Western Siberia, that in winter this distribution is characterized by the presence of high-power ground inversions observed up to the heights of 800 and 600 m, respectively. Besides, in winter, an appreciable decrease of mean temperature and humidity in the direction from south-west to northeast is observed throughout the ABL: the highest temperature and humidity are seen at the station Verkhnee Dubrovo and the lowest ones – at the station Turukhansk.

In summer, the temperature and humidity decrease with the height, however, to the south of 61°N, a 100 m layer of ground temperature inversion or isotherm has been found. As to the spatial distribution of $\bar{t}$ and $\bar{q}$, they decrease from the south to the north throughout the ABL.

The inversion distribution of temperature and humidity with the height in winter period is due to strong radiation cooling and, as a consequence, to drying of the ground air over cold underlying surface under conditions of anticyclonic atmospheric circulation.[3]

A slight rise of temperature in the lower 100-m layer, observed in summer, is due to the appearance in this season of night radiation inversions.

Consider now peculiarities of vertical distribution of mean zonal and meridional wind. Figure 1 shows that in winter in ABL over the entire territory of Western Siberia the radiation fluxes have, on the average, the west component except for the ground 200 m layer in the northwest (st. Turukhansk). In this case, everywhere, the west wind velocity strongly increases with height, in particular, in the lower 600-m layer (from ~ 1 m/s near the Earth surface to 5–8 m/s at 600 m level). However, the intensity of such increase depends greatly on the latitude and longitude of the site; the largest increase of the west wind with height is observed in the vicinity of the station Emel'yanovo, where the wind velocity increase is connected with flowing around the Altai and Sayanskiye mountains. The minimal west wind velocities are observed above the 200 m level at the northeast regions of Western Siberia (st. Turukhansk).

The analysis of vertical distribution peculiarities of the mean meridional wind indicates that, on the average, the south component is dominant in winter in the atmospheric boundary layer over Western Siberia. An important characteristic of the meridional wind velocity distribution (as compared to zonal wind) is the increase of the south wind velocity with height only in the lower (200–300 m) layer. The minimal wind velocities are observed in the northwest part of the considered region (st. Salekhard), and the maximal ones – in its northeast part (st. Turukhansk). Higher this layer, the south wind velocities decrease with the height.

In summer, as in contrast to winter, in the lower 400 m layer of ABL in the central (st. Khanty-Mansiisk, Aleksandrovskoye) and south (st. Omsk, Novosibirsk) regions of Western Siberia zonal flows, on the average, have the east component, however, at velocities close to zero. Very low west winds are observed in the west (st. Verkhnee Dubrovo, Salekhard) and in the east regions (st. Emel'yanovo, Turukhansk), as well as higher 400 m over the entire territory of Western Siberia.

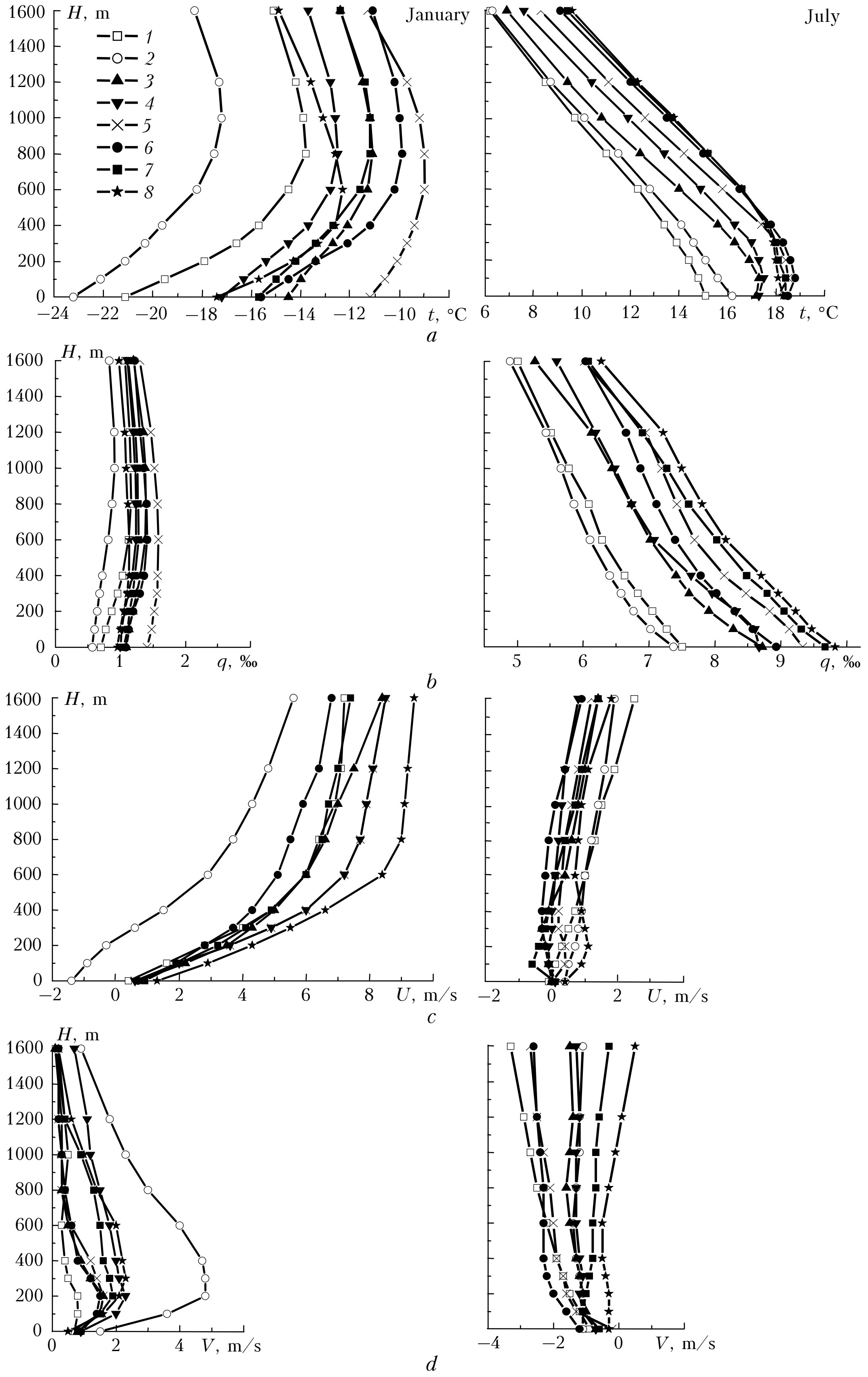

Fig. 1. Vertical distribution of temperature (*a*), air humidity (*b*), zonal (*c*) and meridional (*d*) wind in the atmospheric boundary layer over Western Siberia (*1* – Salekhard, *2* – Turukhansk, *3* – Khanty-Mansiisk, *4* – Aleksandrovskoye, *5* – Verkhnee Dubrovo, *6* – Omsk, *7* – Novosibirsk, *8* – Emel'yanovo).

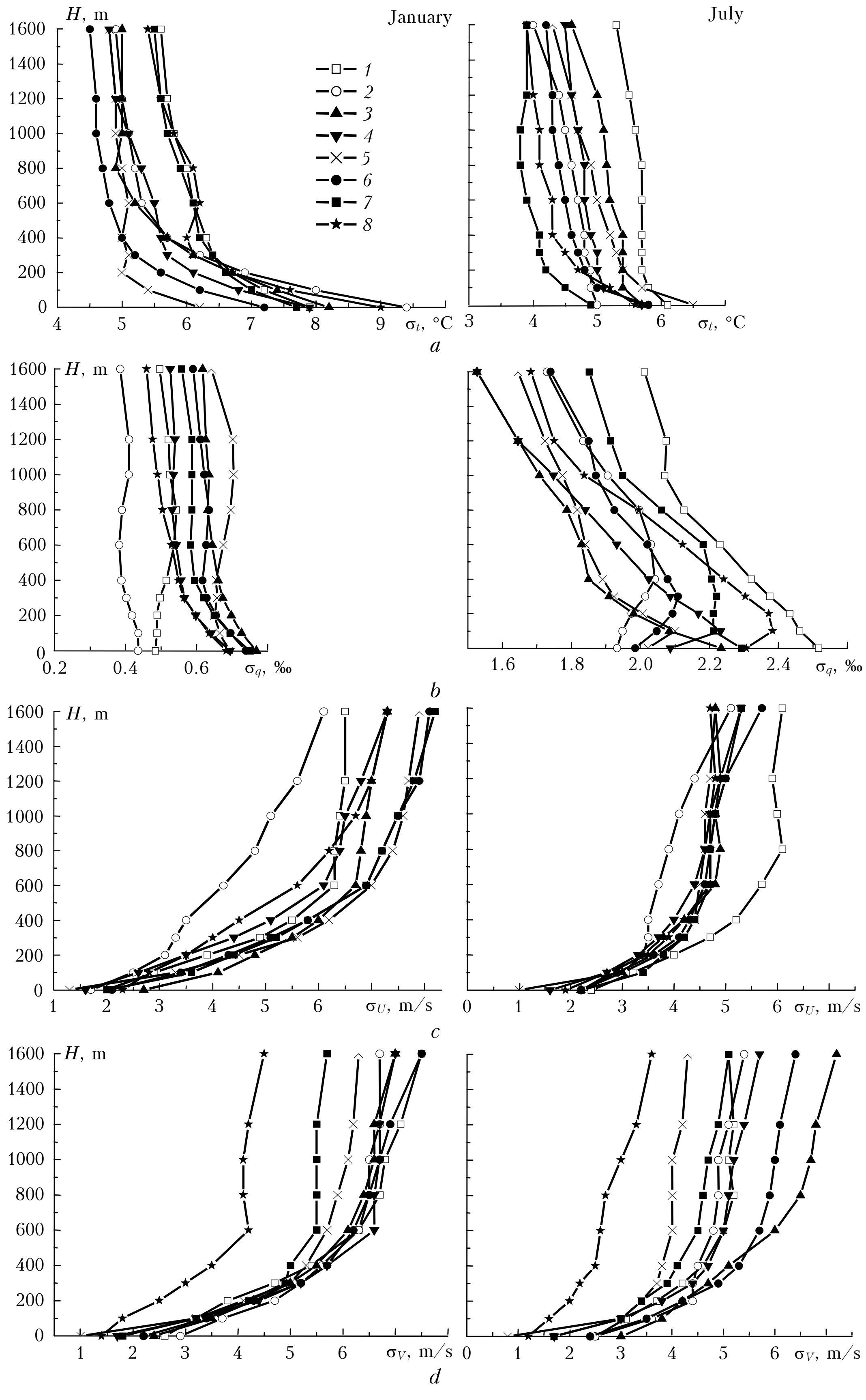

Fig. 2. Vertical distribution of rms deviations of temperature (*a*), air humidity (*b*), zonal (*c*), and meridional (*d*) winds in the atmospheric boundary layer over Western Siberia. Designations are the same as in Fig. 1.

As to the summer distribution of the meridional wind, it characterizes by the north component and small velocity, excluding st. Emel'yanovo higher 1200 m.

3. Peculiarities of variations of vertical profiles of temperature, humidity, and wind in the atmospheric boundary layer

Along with the vertical structure of mean fields, of interest are peculiarities in variability of temperature, humidity, and wind fields. Now we dwell on the analysis of variability of these fields in the atmospheric boundary layer over Western Siberia. For this purpose we analyze Fig. 2, which shows the distribution of rms deviations of temperature, humidity, and orthogonal components of the wind velocity, characterizing possible variations of these meteorological parameters around their means.

It is seen that in winter the variability of temperature and humidity throughout the territory of Western Siberia is rather high, especially close to the Earth surface. It decreases with height, in particular, the temperature variability. As for the air humidity, the minimal variability is typical for northern regions (st. Turukhansk and Salekhard), where the minimal air humidity is observed.

The presence of the maximum of temperature and humidity variability in the atmospheric boundary layer is due to joint action of radiation and circulation factors. Actually, according to Ref. 3, an intensive interlatitudinal and zonal exchange of air masses is observed in winter over the continents of the north hemisphere, which under conditions of strong radiation cooling of the atmospheric boundary layer over the internal areas of continents (among them in Western Siberia), motivating here the formation of strong ground inversions, is responsible for significant variation of temperature and humidity near the Earth surface.

The variation of temperature and humidity considerably decreases from winter to summer, that is typical of the whole atmospheric boundary layer. In this case, distributions of rms deviations of temperature and humidity with height in ABL over Western Siberia have different character. Thus, a decrease of the temperature variability with height is typical in winter throughout the atmospheric boundary layer, however, the variability is less intensive. At the same time, maximal temperature variability is observed in the northwest (st. Salekhard).

The character of humidity variation distribution with height differs. On the whole, the humidity decreases with height more intensively than in winter. However, in the south (st. Verkhnee Dubrovo, Omsk, Novosibirsk, Emel'yanovo) and in the northeast (st. Turukhansk) some rise in humidity variability is observed in the lower (100–400 m) layer.

Some peculiarities are also typical for the variability of the zonal and meridional wind fields. Analysis of Fig. 2 shows that regardless of the season and geographic position of the station the variability of the zonal and meridional wind velocity is insignificant in the boundary layer (σ_U and σ_V are about 1–3 m/s) and greatly increases with height, especially in the lower (400–600 m) layer.

Thus, the above analysis has shown that the vertical structure of fields of mean temperature, humidity and wind, as well as their variability in the atmospheric boundary layer over Western Siberia has both general characteristics and clear peculiarities connected with the season and geographic position of the station.

It should be said in conclusion that the results of the analysis of the inter-level correlation of temperature, humidity, and wind in the atmospheric boundary layer over Western Siberia will be the subject of our next paper.

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