Investigation of wind shear structure and turbulence characteristics in a warm front cloud system using a research aircraft

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Abstract. The manuscript presents the results of study vertical and horizontal wind shears, the spectral characteristics of turbulence in the warm front cloud system using the Yak-42D aircraft-laboratory. Within the As-Cs clouds at altitudes of 3 - 8 km, vertical wind shear increased sharply to 1.5 ms⁻¹ per 100 m. At altitudes of 8 - 9 km, in the jet stream zone, vertical wind shear increased up to significant values of 3.0 ms⁻¹ per 100 m. The maximum horizontal wind shear of 0.3 ms⁻¹ per km was reached in As-Ns clouds at altitudes of 2 - 4 km. Anisotropy of turbulence with a predominance of horizontal wind fluctuations was observed in the stable layer at the altitude of 6000 m. The normalized spectra of the wind speed fluctuations in the lower part of the cloud system (at an altitude of about 3 km) corresponded to the stable layers of the atmosphere. The maximum value of 0.8 at the coherence spectra between the temperature and the vertical wind speed fluctuations was observed at the scales of 1200 m. It is noted that a solid Cs-As-Ns cloud system could be divided into sub-layers, depending on structure of wind shear and turbulence.

1. Introduction

Wind shear, as well as turbulence, accompanies many meteorological processes: development of a planetary boundary layer, atmospheric jet streams, convective motions, breeze circulation, etc. Wind shear and turbulence affect the piloting of aircraft and can cause serious flight accidents. According to ICAO law regulations [7], vertical wind shears are considered to be weak, if they are 0 - 2 ms⁻¹, moderate, if they are within 2 - 4 ms⁻¹, strong, if they are 4 - 6 ms⁻¹, and very strong, if they are over 6 ms⁻¹ (wind shear is calculated with a 30-m height interval). Changes in the longitudinal wind speed component are considered to be safe for aircraft flights, if they are over 5 ms⁻¹ per 600 m of a horizontal flight path.

The currently employed research aircraft Yak-42D “Roshydromet” is equipped with instruments that allow defining the wind vector with a high accuracy and calculating wind shears and turbulent wind speed fluctuations in the atmosphere [1]. The principle of defining the wind speed vector aboard the research aircraft is based on calculating the difference between two vectors, those of the airspeed vector and the aircraft ground speed one. Absolute values of these variables are usually one order larger than the measured difference between them, and therefore, their accurate measurements are especially important. The following instruments are used to define wind speed and direction onboard the Yak-42D research aircraft:

- Inertial navigation system LaserRef-VI which is used to measure heading, roll and pitch angles, and three components of the aircraft ground speed;
- Satellite global navigation system BPSN-2 which is used to determine the geographic coordinates, the track angle and ground speed of the aircraft;
- Hemispherical air pressure probe with a system of pressure transducers, which is used to obtain the value of the airspeed vector, i.e. an absolute magnitude of the airspeed as well as the angles of attack and sideslip.
The aircraft measuring system provides wind speed measurements with an error of not larger than 0.3 m/s\(^2\) at horizontal flight conditions and not larger than 1 m/s\(^2\) during the aircraft maneuvers [9]. This accuracy was verified during numerous field flight and numerical experiments [4], [3]. Random and systematic temperature-wind measurement errors were determined, taking into account various disturbing factors (aerodynamic disturbances, aircraft roll and pitch maneuvers, the impact of cloud particles on the sensors).

The air temperature was measured using a high-frequency temperature sensor (HFTS) which is a hot-wire platinum sensitive element wound on a cruciform frame with a protective Teflon cone. Calculations of true air temperature were made, taking into account the dynamic heating of the air flow during its deceleration on the sensor [1]. The error of true air temperature determination was no more than 0.3 °C during flight segments in clear air or in purely crystalline clouds, and no more than 0.5 °C in clouds with a liquid-droplet fraction. The temperature sensor, as the most inertial one in the system, determined the frequency response of the aircraft measuring system, which was thus about 10 Hz. For a typical speed of the research aircraft of 100 - 150 m/s\(^2\), this corresponds to a spatial scale of wind speed and air temperature fluctuations of 10 - 15 m. Measurements of wind speed and air were supplemented with data from the Russian BPSN-2 satellite navigation system, which made it possible to relate all the obtained data to the geographic coordinates with an accuracy of 0.0003 ° and to the geometric height with an error of not more than 10 m.

All the aircraft measuring systems received signals from a unified time server. The clocks of the on-board computers were synchronized according to these signals with an accuracy of 0.001 s, and a corresponding time was assigned to all measured parameters during the registration [3]. The well-known methods of calculating wind speed components and air temperature, which are described in detail in the textbook [9], were used for the analysis in this paper.

High accuracy aircraft sensors and designed accurate methods for calculating air temperature and wind speed components gave possibility to study thin structure wind speed and air temperature fields at different heights in atmosphere and investigate characteristics of wind shear and atmospheric turbulence. Clouds of different forms (types) severely distort the structure of dynamic structure of the atmosphere (see, for example, [8]), which is reflected in the occurrence of wind shears and turbulence. Thus, the main goal of the present manuscript was revealing of some features of wind speed shear and turbulence structure in cloudy atmosphere.

2. Calculation of wind shear and energy of turbulent fluctuations

The horizontal wind shear along the selected direction is determined through the expression:

$$\frac{\partial V}{\partial L} = \varepsilon_x \left( \frac{\partial V_x}{\partial L} \right) + \varepsilon_y \left( \frac{\partial V_y}{\partial L} \right)$$

(1)

The vertical wind shear is given by:

$$\frac{\partial V}{\partial Z} = \varepsilon_x \left( \frac{\partial V_x}{\partial Z} \right) + \varepsilon_y \left( \frac{\partial V_y}{\partial Z} \right)$$

(2)

where \(\varepsilon_x, \varepsilon_y\) are the horizontal unit vectors of the coordinate system for representing the wind components, \(L\) is the distance along the selected horizontal direction, \(Z\) is the vertical distance (height), \(V_x\) is the latitudinal component of the wind speed, \(V_y\) is the longitudinal component of the wind speed.

The modulus of the horizontal wind shear \(|S|\) is determined based on the wind shear components, using the formula:
he zero isotherm at 12:15, December 17–nd a

is determined though the expression:

and the modulus of the vertical wind shear |W| is determined though the expression:

The energy of turbulent wind speed fluctuations is calculated through the relations:

where the variances of the horizontal $u'$ and $v'$ and vertical $w'$ wind speed fluctuations are:

In formulas (5) and (6), j =1,2, ... N is the number of the values in sequences of wind components for horizontal measuring flight legs, $\sigma_u^2$, $\sigma_v^2$, $\sigma_w^2$ are the dispersions of turbulent fluctuations of the wind speed components, $\nabla_{x,j}$, $\nabla_{y,j}$, $\nabla_{z,j}$ are the calculated regression curves for correspondent wind speed components, $E_h$ and $E_w$ are the energies of the horizontal and vertical of wind speed components fluctuations, respectively.

To calculate the wind shear, parameters of regression lines for wind speed components along the flight path were calculated based on the least squares method. The accuracy of this method was 0.007 ms$^{-1}$ per km for horizontal wind shears and 0.07 ms$^{-1}$ per 100 m for vertical ones. The results of the errors estimating will be published soon.

3. Synoptic situation and flight tracks during investigations

During the period of flight investigations (December 17, 2019), Moscow region was under the influence of two vast pressure systems, a multicenter cyclone over the northern part of Europe and the Scandinavian Peninsula and an anticyclone centered over the Caucasus and Asia Minor. The location of the synoptic vortexes contributed to the appearance of large horizontal pressure gradients and a powerful westerly air transport in the boundary layer and in the middle troposphere. The research aircraft Yak-42D took off from Ramenskoye airport on December 17, 2019 at 12:15 Moscow local time (MLT). The surface air temperature during the taking off was +1.6 °C, and the zero isotherm at the airport area was located at an altitude of 550 m. During the aircraft climb over the area of Voskresensk city and Yegoryevsk city, a continuous As-Cs layer was observed within an altitude range from 3000 to 9000 m (see figure 1). From 12:45 to 13:18 MLT, the aircraft was carrying out observations along the flight lines between Yegoryevsk and Voskresensk at an altitude of 9200 m, above the upper boundary of cirrostratus clouds (Cs). At this time, an onboard measuring system
recorded a horizontal wind speed of up to 250 km h⁻¹, related to an atmospheric jet stream axis directed from northwest to southeast. The jet was also found in radio-sounding data obtained at Ryazan.
radiosounding station (direction and distance to the station are shown at the map in figure 1), which was the closest to the aircraft measuring site. According to the radio-sounding data, there was mainly a stable stratification up to an altitude of 7500 m, and the axis of a jet stream with a 80 ms⁻¹ wind speed was located at an altitude of 9000 - 10000 m. Between 13:20 and 15:10 MLT, the aircraft was descending from a 9000-m to a 600-m levels, carrying out observations over horizontal sampling flight legs oriented along the line between Voskresensk and Yegoryevsk. The main observations were carried out along horizontal sampling legs located approximately 1000 m apart, with flight duration along each of them being 8 - 10 minutes (see figure 1). Overall, measurements were fulfilled along 10 horizontal sampling legs.

During the aircraft descent after 13:30 of MLT, the cloud layering was visually observed below the 8000 m. At the same time, at heights of 8 - 9 km, a thin layer of cirrus and cirrostratus clouds (Ci-Cs) was clearly seen, and below the As cloud layer was located, but at 14:00 MLT upper boundary of the cloudy system has dropped up to level of 6 km. After 14:00 MLT, according to the data of ground-based meteorological radar, precipitation with an intensity of up to 1 mm per hour was recorded, the intensity tending to increase and reaching 3 - 5 mm per hour by 15:00 MLT. This indicated a change in the structure of cloudiness and the appearance of stratus clouds (Ns). During the aircraft landing in the area of Ramenskoye airport, Ns clouds were visually observed, with the lower boundary of 1100 m. Below, at an altitude of 700 - 1000 m, there was observed an inhomogeneous layer of stratocumulus clouds (Sc) and, at an altitude of 300 - 500 m, a layer of ragged rain clouds (Frnb).

Thus, during the period of observations, a dynamic process of cloudiness and weather conditions changing was observed. It was characterized by a passage of a classical warm atmospheric front.

4. Wind shears at different heights in the cloudy zone of the warm front
Calculations of the vertical shear of horizontal wind were made by the regression method, based on the wind speed data obtained during the aircraft climb to an altitude of 9000 m. The value of wind

![Figure 2](image_url)
shear for two horizontal wind speed components and module of wind speed $|W|$ was calculated for each level up to that height with a spatial interval of 500 m.

Figure 2 demonstrates variability of vertical shear of horizontal wind in cloudy system of warm front. The figure also shows vertical distribution of potential temperature $T_p$, wind speed $V$ and wind angle $\delta$, obtained during climb of aircraft. As it clear seen from the figure 1 the aircraft ascended through the As-Cs cloud system. The results of measurements showed that in the sub-cloud layer (practically without any clouds) up to a height of 3 km, the vertical shears of the horizontal wind were rather small, being about 0.10 - 0.30 m$^{-1}$ per 100 m. In the cloud layer at altitudes of 3 – 5.5 km (in the As clouds), the wind shear values sharply increased to significant values of 1.5 m$^{-1}$ per 100 m, becoming negligible at the lower boundary of Cs. In the Cs cloud zone wind shear become significant again, up to values of 1.5 m$^{-1}$ per 100 m. At altitudes of 8 - 9 km, in the jet stream zone, vertical wind shears reached significant values of 3.0 m$^{-1}$ per 100 m. Thus, vertical distribution of horizontal wind shear clearly correspond to cloudy layers, which visually identified as cloud of different types. As also mentioned in literature (see textbook [8] for example) clouds have the influence on the atmosphere around them, which is reflected in the structure of the turbulence. The present studies have shown that cloud systems have also significant effect on the structure of wind shears, which is important both for solving the problems of cloud physics and for ensuring flight safety.

5. Turbulence intensity and horizontal wind shears in warm front cloud system

The descent of the research aircraft was fulfilled inside a slightly different air mass (a Cs-As-Ns cloud system, see figure 1). Measurements at horizontal sampling legs allowed calculating the horizontal wind shears.
shear of horizontal wind speed components and absolute wind shear values as well as estimating the intensity of turbulent fluctuations of wind speed components.

The results shown in figure 2 and 3 give reason to suggest a possibility of detecting some cloud layers inside an almost continuous Cs-As-Ns cloud system. Importantly, this assumption is based on the peculiarities of the wind shear distributions. The horizontal wind shears were the most significant in the Ns clouds (at heights from 1 km to 4 km), where wind shear values were about 0.25 m s⁻² per km. The minimal horizontal wind shear was observed at an altitude of 3000 m in the field of temperature inversion. At this height there was the boundary of a sharp turn of wind direction, the wind angle changing from 240° to 300°. All this has led us to assume that the upper boundary of the layer was at an altitude of 3000 m.

In the overlying layers, inside the As cloud system, the horizontal wind shears increased again up to 0.27 m s⁻¹ per km. Above 6000 m, in the Cs-Ci cloud layer, the horizontal wind shears diminished. At the same altitude, a sharp decrease of the intensity of both horizontal and vertical wind speed fluctuations was noted. Moreover, this made it possible to assume that dynamically (in terms of the structure of wind and fields of turbulence) the clouds of the upper layer located in the zone of the jet stream, significantly differed from the underlying As clouds. It is known [8] that clouds of various forms (types) differ significantly in their dynamics and, especially, turbulent structure. Therefore, presumably, differences in the structure of horizontal wind shears and turbulence in clouds make it possible to reveal individual cloud layers inside the general Cs-As-Ns cloud system.

Variances of wind speed fluctuations, determined for the horizontal sampling legs at different altitudes, were used as characteristics of turbulence intensity. For the Ns cloud layer, which was evidently located at levels between 1 and to 3 km, a maximum of the turbulent energy of the vertical and horizontal wind speed components was observed at an altitude of 3 km. At this level there was an inversion layer, and the corresponding energy maxima for horizontal and vertical components were 1.8 m² s⁻² and 0.5 m² s⁻², respectively. Therefore, the turbulent energy maxima were located near the presumed upper boundary of the Ns layer.

It is well-known [6] that fluctuations of the longitudinal wind speed component receive energy directly from the main flow, but their lateral components get energy as a result of the redistribution one the longitudinal component. For a stable air-mass layer extending up to an altitude of 6000 m, the intensity of vertical wind speed fluctuations is observed to decrease, somewhat increasing in clouds of the upper tier in a jet stream zone. It is evident that under neutral stable conditions, or even stable stratification, the development of convection is suppressed by buoyancy forces, thus the main contribution to turbulence is made by fluctuations of the horizontal wind speed component, which remaining high nearly throughout the entire cloud thickness. A clearly pronounced anisotropy of turbulent fluctuations can also be noted. Usually, turbulence anisotropy is characterized by the parameter \( \frac{2E_u}{E_h} \) [2], [8]. In our experiments, this parameter varied from 0.11 (at an altitude of about 5000 m) up to 0.6 (at an altitude of 3000 m). In an air layer with neutral temperature stratification above 6000 m, this ratio was close to 1 and varied from 1.27 at an altitude of 6000 m to 0.7 at an altitude of 9000 m, while at an altitude of 7000 m it was approximately equal to 1.

6. Spectral characteristics of turbulence in clouds of a warm atmospheric front

Calculations of longitudinal \( \mathbf{u}' \), lateral \( \mathbf{v}' \) and vertical \( \mathbf{w}' \) wind speed components fluctuations and air temperature fluctuations \( \mathbf{T}' \) were carried out using formulas (5) based on the data obtained at the sections of the horizontal steady flight (sampling legs) without significant changes in speed and altitude and with minor changes in the roll and pitch angles (changes in the airspeed of the aircraft did not exceed 20 km per hour, flight altitude - 10 m, and roll and pitch angles - 5°). The typical lengths of the sampling legs were 8 - 10 km, which were enough to obtain statistically significant spectral data. The spectral characteristics of the turbulent fluctuations of the horizontal and vertical wind speed components as well as air temperature fluctuations (spectral densities \( \Phi_u(k) \), \( \Phi_v(k) \), \( \Phi_w(k) \), \( \Phi_T(k) \))
\( \Phi_t(k) \) and spectra of coherence between wind speed components and air temperature fluctuations \( \text{Coh}_{uv}(k) \), \( \text{Coh}_{wT}(k) \) were calculated for horizontal sampling legs at different altitudes based on well-known windowed Fourier transform [10]. All spectral characteristics were presented as dependence on the wave number \( k \) \( (k = \frac{1}{\lambda}, \) where \( \lambda \) was the wave length). Figure 4 demonstrates normalized spectral densities \( \frac{\Phi_u(k)}{\sigma_u^2}, \frac{\Phi_v(k)}{\sigma_v^2}, \frac{\Phi_w(k)}{\sigma_w^2}, \) and \( \frac{\Phi_T(k)}{\sigma_T^2} \) as well as spectra of coherence \( \text{Coh}_{uv}(k) \), \( \text{Coh}_{wT}(k) \) obtained for different flight levels.

The spectra of coherence between air temperature and vertical wind speed fluctuations, shown in figure 4, had maxima with very high amplitudes of about 0.8 at vortex scales of 900 - 1200 m. This value of coherence corresponded to the dip in the normalized spectrum of energy of the vertical wind speed fluctuations. Apparently, the energy of the vertical wind speed fluctuations was suppressed on

![Figure 4](image_url)

**Figure 4.** Normalized spectral densities of fluctuations of the vertical wind speed component \( \frac{\Phi_w(k)}{\sigma_w^2} \), air temperature \( \frac{\Phi_T(k)}{\sigma_T^2} \), the lateral wind speed component \( \frac{\Phi_u(k)}{\sigma_u^2} \), the longitudinal wind speed component \( \frac{\Phi_u(k)}{\sigma_u^2} \), and spectrum of coherence between the longitudinal and lateral wind speed components \( \text{Coh}_{uv}(k) \) and between the vertical wind speed component and air temperature \( \text{Coh}_{wT}(k) \) fluctuations.
these scales by negative buoyancy in a stable air layer. Significant values up to 0.7 were also revealed in the spectrum of coherence between temperature and the vertical wind speed fluctuations, calculated for an altitude of 7000 m. Simultaneously, a maximum of the energy spectrum (spectral densities) of vertical wind speed fluctuations was observed at the same scales. A similar nature of the spectral structure of vertical wind speed fluctuations was characteristic of an unstable air mass in a cloud system at heights of 6 - 8 km. This gives possibility to suggest that the zone of instability in the clouds led to the formation of precipitation. The energy spectrum of vertical wind speed fluctuations for the lower part of the cloud system at an altitude of about 3 km had a slope, which close to the Kolmogorov-Obukhov law for the inertial interval [2].

The horizontal wind speed components were used to determine the values of the turbulent fluctuations of longitudinal and lateral wind speed components (relative to the direction of the mean wind). The spectra of longitudinal and lateral wind speed fluctuations for the lower part of the cloud system (at an altitude of 3 km) had a slope of the curves close to the degree “-2” on scales from 100 to 1000 m. This slope of spectra was typical for the stable layers in the atmosphere [2]. The slope of the energy spectra of longitudinal wind speed fluctuations for the clouds of the upper and middle tier (at heights of 6 and 8 km) was close to the one of Kolmogorov-Obukhov law “-5/3”. The spectrum of lateral and longitudinal wind speed fluctuations for an altitude of 7000 m (close to the axis of the atmospheric jet stream) had maxima on a scale of about 600 m. The same scales corresponded to the significant maximum in the spectrum of coherence which was equal to 0.8. According to the generally accepted theory [6], the main flow transfers energy to longitudinal wind speed fluctuations and, apparently, a high value of coherence indicates the existence of a mechanism that effectively transfers this energy to lateral wind speed fluctuations.

7. Conclusion
Aircraft observations of the dynamic structure of a warm front cloud system, including the altitude distributions of vertical and horizontal wind shears, turbulence intensity, the spectral structure of turbulent wind speed and air temperature fluctuations, were fulfilled in the vicinity of Moscow city.

It was shown that the vertical structure of wind shears and the intensity of turbulence depended on the degree of stability in cloudy atmospheric layers.

A relationship between the dynamic characteristics of wind fields and a cloud system of warm atmospheric front consisting of stratus (Ns), altostratus (As) and cirrostratus (Cs) clouds was revealed. Thus it was demonstrated that a solid Cs-As-Ns cloud system could be divided into sub-layers, depending solely on the characteristics of the dynamic air-mass structure.

The spectral densities of wind speed and temperature fluctuations, calculated for both stable and unstable air layers in clouds, were presented.

Significant peaks in the spectra of coherence between vertical wind speed and air temperature fluctuations, as well as in the spectra of coherence between longitudinal and lateral wind speed fluctuations, were revealed. It was suggested that these peaks were associated with the existence of the mechanisms of energy transfer though vortices of a certain size.

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