Turbulence in the upper troposphere according to long-term satellite measurements and its relationship with climatic parameters

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Abstract. A method is described for determining the characteristics of turbulence zones in the upper troposphere based on the processing of measurement data of the SEVIRI radiometer of second-generation European geostationary meteorological satellites in a 6.2 μm water vapor channel. Their spatial and temporal variability in the time interval 2007–2018 is considered. A significant (by 130–60 %) increase in areas occupied by relatively weak and moderate turbulence and a decrease (by 6–33 %) in areas with strong and very strong turbulence were revealed. The relationship of turbulence zones with the characteristics of jet stream and the temperature of the troposphere is investigated. Significant with a probability of more than 95 % annual variations of area of turbulence zones and most of the characteristics of jet stream have been identified. The most pronounced are in phase annual variations of the turbulence areas with the jet stream area and the velocity gradient and counterphase variations with the latitude and longitude of the centre of the jet stream. The connection between the variability of turbulence and the temperature variability of the upper troposphere is revealed. In this case, the effect of temperature on turbulence manifests itself indirectly through the characteristics of jet stream.

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1. Introduction

Satellite methods for determining the wind field in the atmosphere have long and successfully been used to solve scientific and practical problems. They allow you to determine the vector of horizontal wind speed at different heights. However, the turbulent component of the wind field by these methods, as a rule, is not determined. Knowledge of the spatio-temporal characteristics of turbulence is extremely important for ensuring the safety of aviation flights, as well as understanding the characteristics of stratospheric-tropospheric exchange. In the upper troposphere, mainly the so-called clear air turbulence (CAT) is observed, which is associated in most cases with jet currents. CAT can cause buffeting in aircraft with serious consequences. So, in the USA about 790 cases of CAT are recorded annually, which lead to hundreds of cases of minor injuries and dozens of cases of severe injuries among stewardesses and passengers [1].

The main sources of information about CAT are pilot messages, as well as measurements using equipment installed on aircraft (vertical accelerations, equivalent vertical gust velocities, and vortex dissipation velocity are measured) [2]. For CAT forecasts, the calculations of certain predictors (CAT indices) based on the output of forecasting models [2]. UV lidar development underway to identify areas of CAT [3]. Thus, it can be stated that at present there are no reliable instrumental methods for determining the characteristics of clear air turbulence. Therefore, satellite methods can play a significant role in solving this problem. The method developed to determine the characteristics of atmospheric movements from measurements of geostationary meteorological satellites [4, 5] allows us to establish not only the field of the wind velocity vector, but also the coefficient of mesoscale turbulent diffusion and vorticity on the same scale of air mass movement. This article briefly describes a method for determining the characteristics of turbulence zones in the upper troposphere, explores their spatiotemporal variability in the time interval 2007–2018, the relationship of turbulence zones with the characteristics of jet stream and the temperature of the troposphere as an important climatic parameter.

2. A brief description of the method

The essence of the method described in detail in [4] is to use the inhomogeneities in concentration of water vapor as a conservative impurity as a tracer and to use correlation-extreme algorithms. The results of measurements of the SEVIRI radiometer of the second generation European geostationary meteorological satellites for the period 2007–2018 in the water vapor channel 6.2 microns with high temporal (15 min) and spatial (3–6 km) resolution are used as initial information. This channel has a maximum weight function for mid-latitude conditions of approximately 350 hPa. In this case, the half-width of the weight function is approximately 300 hPa [6]. The calculation results refer to the level of 350 hPa.

The main calculated characteristic is the coefficient of horizontal mesoscale turbulent diffusion K_{ed}, calculated on the basis of the analysis of spatial and spatio-temporal structural functions of the radiation field received by a satellite radiometer. A priori error in calculating K_{ed} lies in the range $(3.2–6.4)\cdot 10^3$ m^2/s [4]. To validate the values determined by satellite data, the results of [7] were used, in which an analytical description of the coefficient of relative turbulent diffusion was obtained on the basis of empirical expressions for the structural functions of wind speed in the upper troposphere. It was shown that in the range of scales of 20–150 km, the calculated average K_{ed} values are in better agreement with the theoretical Golitsyn curve, and for large scales, with the Richardson–Obukhov curve [4].

The calculations for the Northern Hemisphere were carried out at the grid nodes with a step of 10 pixels in three consecutive images, separated by a time interval of 15 minutes in the computational region 0–60°N, 55°W–55°E. In addition to the horizontal mesoscale turbulent diffusion coefficient, the areas of turbulence zones (S_{ed}) were calculated, in which the K_{ed} values vary within certain limits. After obtaining the series of areas of turbulence zones with a time step of $\Delta t = 1$ h, they were preliminarily analyzed for eliminating outliers ($\pm 3\sigma$, where σ is the standard deviation from the average value), which can be due to both errors in the initial satellite data and calculation errors. At the outlier points, the values of area were replaced by their average values. For the subsequent analysis, arrays of average daily and monthly average areas of turbulence zones were formed and the methods of correlation and wavelet analysis were used.

3. Results of calculations and discussion

According to previously performed limited calculations for various atmospheric conditions, K_{ed} in the upper troposphere vary over a wide range — from 10^4 to 10^6 m^2/s [4, 8]. For the subsequent analysis, the following gradations of turbulence were introduced: weak ($3\cdot 10^4 > K_{ed} \geqslant 10^4$ m^2/s), moderate ($10^5 > K_{ed} \geqslant 3\cdot 10^4$ m^2/s), strong ($3\cdot 10^5 > K_{ed} \geqslant 10^5$ m^2/s) and very strong ($10^6 > K_{ed} \geqslant 3\cdot 10^5$ m^2/s).

3.1. Spatio-temporal variability of turbulence zones

As the analysis shows, zones of the upper troposphere with a horizontal mesoscale turbulent diffusion coefficient of $K_{ed} \geqslant 10^4$ m^2/s, taking into account the standard deviation, can occupy up to 50 % of the visible from a satellite northern hemisphere, and with $K_{ed} \geqslant 10^6$ m^2/s, only 0.5 %. The largest area (about 30 %) is moderate turbulence, followed by strong turbulence (~15 %), weak (less than 10 %) and very strong (~3 %) (Figure 1). As can be seen in figure 1, this type of distribution of the areas of zones with different gradations of turbulence in the upper troposphere is characteristic of both the Atlantic and Western and Eastern Europe and the European territory of the Russian Federation.

The interannual and seasonal variability is characteristic of all monthly average areas of the turbulent zones. Table 1 summarizes the change in the average monthly area of turbulence zones for the period 2007–2018. Bold text indicates changes in characteristics for which a linear trend is significant with a probability of 95 % or higher. It should be noted the significant, more than 2-fold increase in area with weak turbulence and an increase of more than 50 % in area with moderate turbulence. The area with very strong turbulence decreased over the considered interval by more than 30 %, and area with strong turbulence did not change significantly.

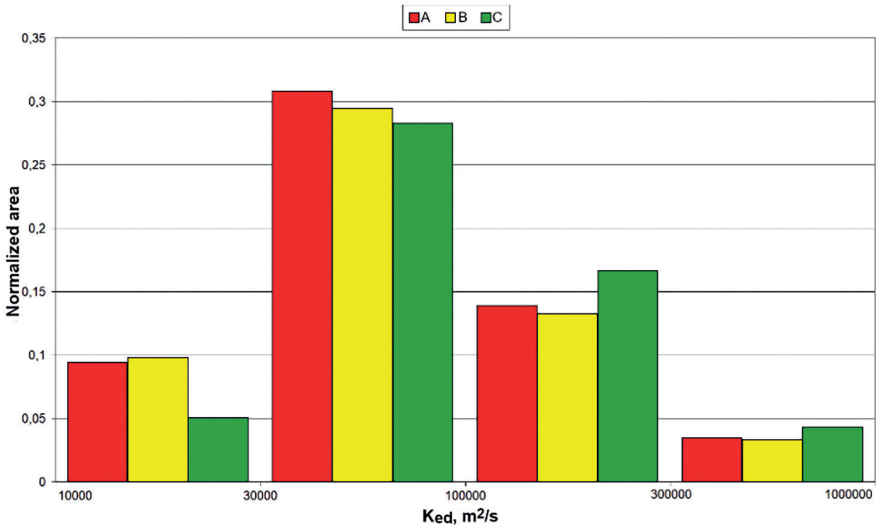

Figure 1. Distribution of average values of normalized areas in the Atlantic (A), Western and Eastern Europe (B) and the European territory of the Russian Federation (C), characterizing weak, moderate, strong and very strong turbulence for the period 2007–2018.

Table 1. Changes in the characteristics of turbulence zones for the period 2007–2018

Characteristic of turbulence	Relative change, %
Area of weak turbulence	132
Area of moderate turbulence	56
Area of strong turbulence	–6
Area of very strong turbulence	**–33**

3.2. The relationship of the areas of turbulent zones with the characteristics of jet streams

The results of cross-wavelet analysis reveal significant annual variations in the areas of turbulence zones and in most jet stream characteristics with a probability of more than 95 %. The method for calculating the characteristics of jet stream from satellite measurements is described in detail in [9]. The connection between the annual variations in areas of strong and very strong turbulence with the area of the jet stream (S_{jet}), the wind velocity gradient on the cyclonic side (G_p), latitude (φ) and longitude (λ) of the centre of the jet stream is most pronounced. In this case, the annual variations of S_{ed} with S_{jet} and G_p occur in phase, and with φ and λ in antiphase (figure 2).

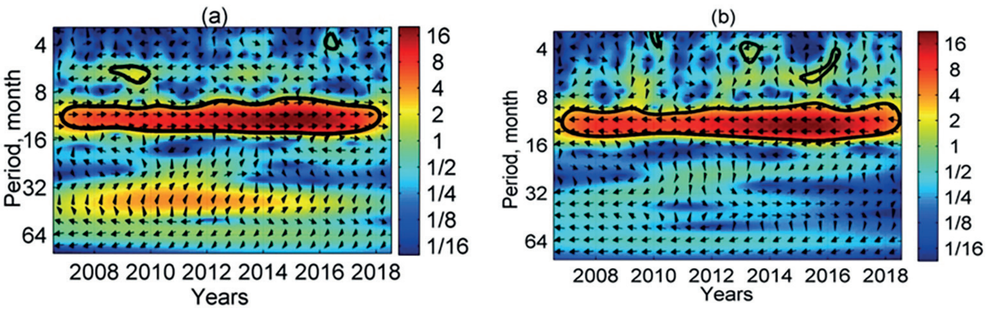

Figure 2. Results of a cross-wavelet analysis of the G_p series and the area of the zones of strong turbulence (a), φ and the area of the zones of strong turbulence (b) in the entire considered spatial region. Explanations for the figure are given in the text.

Those, as the centre of the jet stream shifts north and east from its long-term mean position, the areas of strong and very strong turbulence decrease. And vice versa, with a shift to the south and west — increase. Moreover, the connection with λ is much weaker than with φ.

Using the method for estimating atmospheric and ionospheric variability described above and in [10], the manifestation of activity of atmospheric waves of different time scales (planetary waves, tides, internal gravitational waves) at the heights of the mesopause and F2-region of the ionosphere during the SSWs was analyzed. The obtained values were compared to the seasonal average values for each month, obtained from long-term measurements in 2008–2015 (table).

On all presented waveletograms the arrows show the relationship between phases of time series: to the right — in phase; to the left — in antiphase; downwards, variations of the first row (G_p and φ) outstrip variations of areas of turbulence zones by 90° (i.e. on a quarter of the period); upwards, they are behind by 90°. The degree of correlation of the analyzed series (color scale) is given in relative units. A thick black line draws out the areas with a confidence interval of more than 95 %.

3.3. The relationship of the areas of turbulent zones with the temperature of the troposphere

Cross-waveletograms clearly show occurring in counterphase significant (>95 %) annual variations of areas of strong and very strong turbulence with troposphere temperature (T) at all levels from 200 to 500 hPa in the latitudinal zone from 40 to 60°. In contrast, annual variations in areas of strong and very strong turbulence with a temperature difference between low and high latitudes at 200 and 500 hPa occur in phase with correlation coefficients from 0.6 to 0.8. For individual time intervals, semiannual variations of area of strong and very strong turbulence with a specified temperature difference between low and high latitudes at 500 hPa are in counterphase.

Figure 3 presents, as an example, the results of a cross-wavelet analysis of the relationship between the area of strong turbulence and the temperature at 300 hPa and the temperature difference between low and high latitudes at 500 hPa.

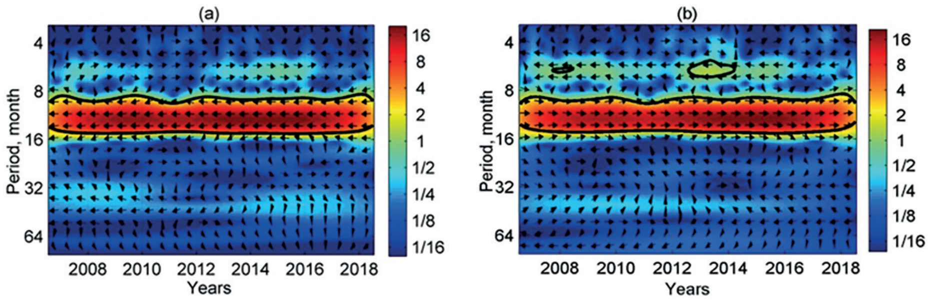

Figure 3. Results of a cross-wavelet analysis of the area of strong turbulence with a temperature at 300 hPa (a) and temperature difference between low (0°) and high (80°) latitudes at 500 hPa (b).

A detailed analysis shows that the influence of troposphere temperature on the area of turbulent zones manifests itself indirectly through the characteristics of jet stream, primarily through the velocity gradient (G_p) and the area of the jet stream (S_{jet}). Indeed, as shown in [10], G_p and S_{jet} decrease at all levels with an increase in T. Since the annual fluctuations of strong turbulence and G_p and S_{jet} are in phase, the annual fluctuations in T and strong turbulence will be in counterphase, as is observed. The same applies to very strong turbulence. Another situation observed with the temperature difference between low and high latitudes. Their annual oscillations are in phase with G_p and S_{jet}; therefore, the phase matching of temperature difference oscillations with the area of strong turbulence is noted.

4. Conclusion

Calculating the wind field in the troposphere on the basis of measurement data of the SEVIRI radiometer in the 6.2 μm water vapor channel makes it possible to identify turbulence zones in the upper troposphere and study their characteristics and dynamics with high temporal and spatial resolution. A joint study of the variability of the areas of turbulence zones in the Northern Hemisphere in the satellite viewing zone with the variability of the characteristics of jet streams and the temperature of the upper troposphere revealed a number of patterns, the main of which are as follows.

1. From 2007 to 2018 in upper troposphere average monthly area with the coefficient of horizontal turbulence diffusion $K_{ed} \geqslant 10^4$ m^2/s is about 50 % of the Northern hemisphere region visible from the satellite.
2. The largest area (about 30 %) is occupied by areas with moderate turbulence, in which $10^5 > K_{ed} \geqslant 3 \cdot 10^4$ m^2/s.
3. On the considered time interval there is a significant (130–60 %) increase in the area occupied by relatively weak and moderate turbulence and a slight decrease (by 6–33 %) in areas with strong and very strong turbulence.
4. There is a close relationship with a probability of more than 95 % between the temporal variability of the area of turbulence zones and most characteristics of jet streams of the upper troposphere.
5. The relationship between variability of turbulence and temperature of the upper troposphere is clearly noticeable. In this case, the effect of temperature on turbulence is most likely mediated through dynamic parameters, in particular, through the characteristics of jet streams.

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