Satellite-derived estimations of the clear-air turbulence in the upper troposphere

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Abstract. The paper presents the results of a study of turbulence zones in the upper troposphere of the Northern Hemisphere based on measurements from European geostationary meteorological satellites in 2007-2018. The essence of the method for determining the zones of turbulence is the use of inhomogeneity’s of concentration of water vapor as tracers and the use of correlation-extremal algorithms. Turbulence zones with a horizontal mesoscale turbulent diffusion coefficient $K_{ed} \geq 10^4$ m²/s can occupy up to 50% of the Northern Hemisphere area visible from satellites. It is shown that in analyzed time interval there is a significant (by 60-120%) increase in areas occupied by relatively weak and moderate turbulence and a slight decrease (by 6-33%) in areas with strong and very strong turbulence. The temporal variability of these zones and their relationship with the characteristics of jet streams and some climatic parameters are analyzed. A statistical model of the temporal variability of the turbulence zone areas has been built. It is shown that the multiple linear regression model with jet stream characteristics as predictors describes up to 68% of variability of zones of strong turbulence. The use of climatic parameters as predictors makes it possible to describe up to 74% of the temporal variability of strong turbulence zones.

1. Introduction

In the atmosphere at altitudes of 6-11 km there is so-called Clear Air Turbulence (CAT). It is mainly associated with jet streams with very strong vertical and horizontal shears of wind speed. The CAT can pose a serious threat to aircraft traveling at specified altitudes. It can cause pitching, manifested in the form of tremors, frequent and small jolts or throws of the aircraft in different directions, including up and down [1]. According to [2, 3], the probability of encountering CAT and orographic turbulence caused by the air flow over the mountain range in the upper troposphere can exceed 80%. Turbulence is costly for airlines: the annual economic damage from it for US carriers varies from 100 to 200 million dollars [3].

Therefore, the problem of diagnosing and predicting atmospheric turbulence is one of the most important problems of aviation meteorology. The difficulty is that CAT zones cannot be visually identified, unlike turbulence zones in clouds. They are also not identified by the aircraft radars. The main sources of information about CAT are reports from pilots, as well as measurements of vertical accelerations, equivalent vertical gust velocities, vortex dissipation velocity using equipment installed on aircraft, which are transmitted within the AMDAR (Aircraft Meteorological Data Relay) program (https://public.wmo.int/en/programmes/global-observing-system/). It should be noted that this information is mainly of a qualitative nature, identifying turbulence in the form of gradations – weak, moderate, strong, extreme [4]. The calculations of certain predictors (CAT indices) are most often used.
based on predictive models [1]. It can be stated that at present there are no reliable instrumental methods for determining the characteristics of turbulence in a clear air.

The method we have developed for processing satellite information allows us to identify turbulence zones, including CAT, in the upper troposphere in quasi-real time by the movement and evolution of atmospheric tracers [5]. This article describes shortly the method for determining turbulence zones in the upper troposphere and analyzes the temporal variability of these zones in 2007 - 2018. Their relationship with the characteristics of jet streams and some climatic parameters is analyzed, and simple statistical models are described.

2. Initial data and methods used
The data of SEVIRI radiometer (Spinning Enhanced Visible and Infrared Imager) of the European geostationary meteorological satellites of the second generation Meteosat 8–Meteosat 10 for the period 2007–2018 was used as the initial satellite information. Turbulence zones are determined on the basis of calculating horizontal mesoscale turbulent diffusion coefficient $K_{ed}$ in the upper troposphere. The essence of the method, described in detail in [5, 6], consists in the use of inhomogeneity's of the field of concentration of water vapor as a conservative tracers and the use of correlation-extremal algorithms. These algorithms, based on calculations of the characteristics of spatial and spatio-temporal structural functions, allow us to determine on a single spatial scale the components of the horizontal velocity of tracer, vorticity and the coefficient of horizontal mesoscale turbulent diffusion $K_{ed}$.

The main elements of the method are:
- The 6.2 µm water vapor channel of SEVIRI radiometer is used. The spatial resolution of the images at the subsatellite point is 3 km, at the boundaries of the calculated area – approximately 2 times worse.
- The values of the coefficient of horizontal mesoscale turbulent diffusion $K_{ed}$ are calculated from 2 images, separated by a time interval of $\Delta t = 15$ min at grid points with a step of 10 pixels in the region of 0–60 N, 60W – 60E. The area occupied by turbulence with different ranges of $K_{ed}$ variation is calculated. The calculation results are attributed to the level of the maximum weight function of the radiometer at a wavelength of 6.2 µm (approximately 350 hPa, about 8 km for mid-latitude conditions).
- The results of [7] were used to validate the $K_{ed}$ values from satellite data.

The following characteristics of jet streams were used as predictors for constructing the first version of the statistical model of turbulence variability: the average area of the jet stream ($S$); maximum wind speed ($V_m$) on the axis; latitude ($\phi$) and longitude ($\lambda$) of the center of the jet stream area; the maximum gradient (shear) of the horizontal wind speed on the cyclonic side ($G_c$) and on the anticyclonic side ($G_a$); the effective "life" time of the jet stream ($T$) [8].

In the second version of the statistical model the climatic parameters are used as predictors:
- monthly mean quasi-zonal (averaged over the longitudinal region 70W – 70E) tropospheric temperature ($T_r$) values at different levels according to the NCEP / NCAR reanalysis data [9] and their differences at levels 200 and 500 hPa ($\Delta T200$ and $\Delta T500$) between low (0°) and high north (80°) latitudes;
- monthly mean area of Arctic sea ice ($S_{ice}$) according to NOAA data (ftp://sidads.colorado.edu/DATASETS/NOAA/).

Relationships between turbulence zones and predictors were analyzed using cross-correlation wavelet analysis [10, 11]. Ridge regression and stepwise regression methods were used to assess the collinearity of predictors and to construct multi-regression models. Preliminarily, the time series of turbulence zones as well as used predictors were standardized and a linear trend was excluded from the series.

3. Main results and discussion
3.1 Temporal variability and parameters of turbulence zones
Calculations showed that the $K_{ed}$ values lie mainly in the range $(10^4 - 10^6)$ m$^2$/s. Figure 1 gives an idea of average turbulized zones for the considered time interval. It can be seen that turbulence zones with
$K_{ed} \geq 10^4 \text{ m}^2/\text{s}$ can occupy up to 50% of the Northern Hemisphere visible from the satellite, and with $K_{ed} \geq 10^6 \text{ m}^2/\text{s}$ only 0.5%.

Figure 1. Average value of Northern Hemisphere area occupied by turbulence with different values of $K_{ed}$ in 2007–2018.

Let us consider the variability of the monthly average characteristics of turbulence zones. For further analysis, we introduce gradations of turbulence based on ranges of $K_{ed}$ values (in m$^2$/s): weak turbulence ($3 \times 10^4 > K_{ed} \geq 10^4$), moderate turbulence ($10^5 > K_{ed} \geq 3 \times 10^4$), strong turbulence ($3 \times 10^5 > K_{ed} \geq 10^5$) and very strong turbulence ($10^6 > K_{ed} \geq 3 \times 10^5$). Analysis shows that the largest area (25% of the Northern Hemisphere viewed from a satellite) falls on moderate turbulence, followed by strong (10%), weak (8%) and very strong (2%) turbulence. Almost all areas of turbulent zones are characterized by noticeable interannual and seasonal variability. Since 2007 the weak turbulence area has increased more than 2 times, moderate turbulence - more than 50%. At the same time, the areas of strong turbulence and very strong turbulence decreased by 6% and 33% respectively.

In what follows, we will consider the characteristics of strong turbulence. Turbulence zones in the first approximation can be presented in the horizontal plane by ellipses. According to the calculations, the characteristic parameters of the zones of strong turbulence are as follows: the minimum size is (100 km × 50 km), the maximum size is (2000 km × 600 km), the average size is (600 km × 250 km), and the characteristic “life” time is (0.5 - 3) hours.

3.2. Relationship with jet streams characteristics

There should be a relationship between the parameters of the turbulence zones and the characteristics of jet streams. Such relationships are clearly manifested with the jet stream area ($S$), the jet stream velocity gradient on the cyclonic side ($G_c$), and the jet stream center latitude ($\phi$) [12]. Cross-wavelet analysis reveals clearly pronounced co-phase oscillations with a period 12 months for the $S$ and $G_c$ series with the area of turbulence zones. The counterphase oscillations of the $\phi$ series and the area of turbulence zones are also clearly manifested. Thus increasing jet stream area and velocity gradient leads to an increase in the turbulence zones area, which is quite natural, and the poleward displacement of the position of the jet stream causes a decrease in the area of turbulence zones [12].
3.3. Relationship with basic climatic parameters

The relationship between strong turbulence area and the temperature characteristics of upper troposphere and Arctic ice area is well traced. Figure 2 shows the results of a cross-wavelet analysis of the area of strong turbulence with the specified climatic parameters, as well as the time course of these characteristics. The arrows show the relationship between the phases of the time series: to the right - in phase, to the left - in counterphase. The degree of correlation of the analyzed series (color scale) is given in relative units. The bold black line marks the boundaries of the region with a confidence interval of more than 90%. Considering the above and taking into account the results of [13], in which the relationship between the characteristics of jet streams and the temperature characteristics of the troposphere and the area of Arctic sea ice is studied, it should be stated that the relationship between the area of strong turbulence and the main climatic parameters acts, from our point of view, indirectly - through the characteristics of the jet stream, primarily through its area and velocity gradient.

![Figure 2. Cross-correlation wavelet transform of strong turbulence \( T_s \) and ice area \( S_{ice} \), (a), and temperature difference \( \Delta T_{200} \) at 200 hPa (b). Upper figures show original time series.](image)

3.4. Statistical model

Based on the multiple linear regression analysis, two versions of statistical model was designed for temporal variability of strong turbulence area. The characteristics of jet streams were used as predictors for constructing the first version of the model. The temperature characteristics of the troposphere and the area of Arctic sea ice were used for the second model. Time series of area of turbulence zones, as well as predictors, were presented as standardized series with removed linear trend. Preliminary calculations by the ridge regression method showed the absence of collinearity of the predictors.

To construct a statistical model the method of stepwise multiple regression was applied. The stepwise multiple regression technique is based on the iterative procedure of selection of possible predictors and estimation of magnitude and significance of the regression coefficients. As a result, the predictors with the largest contribution to the explained variance were included in model and predictors whose contribution was less than 1% were excluded. Figure 3 shows the dependence of the explained variance...
variance for predictors with the largest contribution. The model with the jet stream predictors describes variations in strong turbulence with a coefficient of determination $R^2 = 0.68$ and model with the climatic predictors - with $R^2 = 0.74$. The regression coefficients for models are shown in the table.

### Table. Parameters of statistical models. In brackets 95% confidence interval

| Jet stream predictors | Regression coefficient | Climatic predictors | Regression coefficient |
|-----------------------|------------------------|---------------------|------------------------|
| 1 Area ($S$)          | 0.58 (0.24)            | 1 $\Delta T200$    | 0.55 (0.20)            |
| 2 Center latitude ($\phi$) | -0.46 (0.23)         | 2 $\Delta T500$    | 0.35 (0.29)            |
| 3 Gradient ($G_c$)    | -0.06 (0.07)           | 3 $S_{ice}$        | 0.35 (0.19)            |
| 4 Maximum wind speed ($V_m$) | -0.04 (0.10)       | 4 $T_{tr}$         | 0.31 (0.27)            |
|                       | Variances explained   |                     | 0.68                   |
|                       | Variances explained   |                     | 0.74                   |

It can be seen that the quality of both versions of the model is quite high, which indicates the dominant role of the jet stream area and temperature difference in the temporal variability of zones of strong turbulence. It should be noted that the time series analyzed in the article have a prevailing annual harmonic, which could lead to rather high estimates of correlations. To estimate the contribution of long-period variations the approach [14] was used. For this, seasonal variations and oscillations with periods from 3 to 20 months in the series of strong turbulence and predictors were filtered out. The results of these calculations confirm the conclusion about the predominant influence of the area and latitude of jet streams and temperature gradients between low and high latitudes on the area of strong turbulence.
4. Conclusion

The method developed for processing atmospheric sounding data obtained by geostationary meteorological satellites in the absorption band of water vapor with a center at 6.2 μm makes it possible to identify turbulence zones of different intensities in the upper troposphere. The main restriction of the method consist in a limited altitude range (200-500 hPa), determined by the type of the radiometer contribution function in the channel of 6.2 microns, as well as the spatial scale of the determined turbulent characteristics (mesoscale).

Analysis of the relationship between turbulence zones, jet streams characteristics and basic climatic parameters allow us to draw the following conclusions.

1. The average area of zones with a horizontal mesoscale turbulence coefficient $K_{ed} \geq 10^4 \text{m}^2/\text{s}$ in the upper troposphere in 2007–2018 is about 50% of the northern hemisphere visible from the satellite.
2. The largest area (on average 25%) is occupied by areas with moderate turbulence, in which $10^5 \text{m}^2/\text{s} > K_{ed} \geq 3 \times 10^4 \text{m}^2/\text{s}$.
3. In the considered time interval there is a significant (by 120-60%) 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. A regression model with the jet stream characteristics as predictors describes up to 68% of the temporal variability of strong turbulence area.
5. A regression model with the climatic predictors describes up to 74% of the temporal variability of strong turbulence area.

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References

[1] Shakina N P and Ivanova A R 2016 Forecasting meteorological conditions for aviation (Moscow: Triada Ltd p 312)
[2] Meneguz E, Wells H and Turp D 2016 An automated system to quantify aircraft encounters with convectively induced turbulence over Europe and the Northeast Atlantic J Appl. Meteorol. Climatol. 55 (5) 1077–89
[3] Williams P D 2017 Increased light, moderate, and severe clear-air turbulence in response to climate change Advances in atmospheric sciences. 34 576-586.
[4] WMO No. 306: Manual On Codes 2015
[5] Nerushev A F and Kramchaninova E K 2011 Method for Determining Atmospheric Motion Characteristics Using Measurements on Geostationary Meteorological Satellites Izvestiya, Atmospheric and Oceanic Physics 47 9 1104–1113
[6] Nerushev A F and Ivango, odsky R V 2019 Determination of turbulence zones in the upper troposphere based on satellite measurements Sovremennye problemy distantsionnogo zondirovaniya Zemli iz kosmosa 16 1 205–215
[7] Golitsyn G S 2001 An Explanation of the Relative Eddy Diffusion Law in the Atmosphere and on the Ocean Surface Dokl. Earth Sci. 381 8 939–941
[8] Ivango, odsky R V and Nerushev A F 2014 Characteristics jet streams upper troposphere by measurements of the European geostationary meteorological satellites Sovremennye problemy distantsionnogo zondirovaniya Zemli iz kosmosa 11 1 45-53
[9] Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Saha S, White G, Woollen J, Chelliah M, Janowiak J, Mo K C, Wang J, Leetmaa A, Reynolds R, Jenne R, Kung E and Saisalsten D 1996 The NCEP/NCAR Reanalysis 40-year Project Bull. Amer. Meteor. Soc. 77 437-471.
[10] Torrence C and Compo G P 1998 A practical guide to wavelet analysis Bull. Am. Meteorol. Soc. 79 61–78
[11] Grinsted A, Moore J C and Jevrejeva S 2004 Application of the cross wavelet transform and wavelet coherence to geophysical time series Nonlin. Processes Geophys. 11 561–566
[12] Nerushen A F, Visheratin K N and Ivangoordsky R V 2020 Characteristics of the upper troposphere wind field according to the satellite measurements and their connection with climatic parameters *IOP Conf. Series: Earth Environ. Sci.*, **606** 012041

[13] Nerushen A F, Visheratin K N and Ivangoordsky R V 2019 Dynamics of High-Altitude Jet Streams from Satellite Measurements and Their Relationship with Climatic Parameters and Large-Scale Atmospheric Phenomena *Izvestiya, Atmospheric and Oceanic Physics*, **55** 9 1198–1209

[14] Nerushen A F, Visheratin K N and Ivangoordsky R V 2021 Statistical model of time variability of characteristics of northern hemisphere high-altitude jet streams based on satellite measurements *Izvestiya, Atmospheric and Oceanic Physics*, **57** 4 401-413