Characteristics of the upper troposphere wind field according to the satellite measurements and their connection with climatic parameters

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Abstract. The results of the study of the spatio-temporal variability of the main characteristics of jet streams and turbulence zones in the upper troposphere of the Northern Hemisphere according to measurements from European geostationary meteorological satellites for the period 2007 - 2018 are presented. Their relationship with the essential parameters of the Earth's climate system — the temperature of the troposphere, the area of sea ice, and also large-scale atmospheric phenomena is considered. It has been shown that over the past 12 years there has been a significant increase in the area of regions occupied by relatively weak and moderate turbulence and a slight decrease in areas with strong and very strong turbulence. Based on the cross-wavelet analysis in the time-frequency space, the relationships between the variations in the areas of the turbulent regions and the majority of the characteristics of jet streams are revealed. A close relationship has been established between the characteristics of jet streams and the areas of turbulent zones with the temperature of the upper troposphere. In this case, the effect of temperature on the area of turbulent zones manifests itself indirectly through the characteristics of jet streams. A significant association of variations in the average area of the jet stream and the latitudinal position of its center with the area of sea ice are noted. According to spectral and wavelet analysis of the characteristics of jet streams, along with annual and quasi-biennial oscillations, short-period oscillations are observed with periods in the range of 10-40 days, which can be interpreted as a manifestation of Rossby waves.

1. Introduction

Global climate change affects all atmospheric characteristics, including dynamics. The important element of the upper tropospheric dynamics are jet streams (JS) and the associated clear-air turbulence (CAT). Due to tremendous kinetic energy, JS represent an attractive natural source of renewable energy [1, 2]. Thus, the power of a relatively “slow” jet stream at a speed of 50 m/s at an altitude of 9 km and dimensions of 100 km in width and 2 km in height is $5 \times 10^{12}$ W = 5 TW. For comparison, we indicate that the need of mankind in providing energy in 2010 amounted to about 17 TW [2]. A number of abnormal weather phenomena are associated with jet streams also [1]. CAT poses a significant danger to aviation flights [3]. Caused by turbulence, repeatability of the chatter in the upper troposphere over the territory of the Russian Federation occurs at heights of 8–12 km and can reach up to 20% in the southern regions [4]. 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 [5]. According to recent studies, 84% of cases of turbulence in the upper troposphere occur in clear air conditions [6]. Knowing the real position
of the jet stream, its characteristics and associated CAT zones is important for solving a number of practical problems, in particular safe flight zones in the upper troposphere.

A review of recent works on the impact of climate change on JS dynamics, performed mainly on the basis of theoretical modeling or processing of reanalysis data, is contained in [7, 8]. Estimates of the effect of doubling the carbon dioxide content in the atmosphere compared with the pre-industrial period on the frequency of occurrence of turbulence are given in [9].

Using information from geostationary meteorological satellites with a high temporal resolution (~15 min) [10], it is possible to identify zones of jet streams and turbulence at a certain atmospheric level, and also to study the features of their spatial - time variability and connection with the essential parameters of the Earth's climate system. The present work is devoted to the presentation of the main results obtained in recent years in the survey zone of European geostationary meteorological satellites for the Northern Hemisphere region.

2. Initial data and calculation methods

The SEVIRI radiometer sounding data (Spinning Enhanced Visible and Infrared Imager) of meteorological satellites Meteosat 8–Meteosat 10 for the period 2007–2018 is used as initial satellite information. Jet streams and turbulence zones are determined by calculating the field of the horizontal wind speed vector and the coefficient of horizontal turbulent diffusion from the movements and evolution of atmospheric tracers - water vapor concentration inhomogeneities. The method based on the correlation-extreme algorithms is described in detail in [10]. The field of the horizontal wind velocity vector (V) in the upper troposphere and the horizontal mesoscale turbulent diffusion coefficient (K_{ed}) are calculated from measurements in the water vapor channel centered at 6.2 μm at the grid nodes with 10 pixel increments over three consecutive images separated by an interval 15 minutes. The calculation results relate to the maximum level of the weight function of the radiometer (approximately 350 hPa). The absolute error in calculating the module of horizontal wind speed by the developed method does not exceed 8 m/s, and the a priori K_{ed} error lies in the range (3.2 - 6.4) × 10^{-3} m^2/s [10]. After calculating the horizontal wind speed vector with a time step of 1 hour, their localization areas are identified and the following average daily and monthly average characteristics are calculated [11]: JS average area (S), maximum wind speed (V_{m}) on the axis, the latitude (φ) and longitude (λ) of the center of the JS region, the maximum gradient (shear) of the horizontal wind speed from the side facing the pole (G_{p}) and from the opposite side (G_{b}) and others. The algorithm for automatic search of jet streams and calculation of their characteristics is described in detail in [11].

According to previous calculations [10], the K_{ed} values in the upper troposphere vary mainly from 10^{-3} m^2/s to 10^{-2} m^2/s, and its maximum values in areas of increased turbulence exceed background values by 8–10 times. Note that both horizontal and vertical turbulent pulsations influence the flight conditions of aircraft in the CAT zones. As a rule, the ratio of the vertical thickness (ΔH) and horizontal length (Δx) of the CAT sections amounts to ΔH/Δx ~ 10^{-3} [12, 13]. To determine the turbulent regions with a time step of 1 h, the areas of turbulence zones in which K_{ed} ≥ K_{m} were calculated. The values 10^{-4}, 3×10^{-4}, 10^{-5}, 3×10^{-5}, 10^{-6} m^2/s were taken as K_{m}. The calculations of the area of turbulence zones were carried out both for the region of the Northern Hemisphere (0° - 65° N, 65° W - 65° E), and for each of the 3 selected areas. Region A with longitude boundaries (65° - 10° W) encompasses the atmosphere over the Atlantic Ocean, region B with borders (10° W - 30° E) includes Western and Eastern Europe, region C (30° - 65° E) captures the European territory of the Russian Federation to the Urals. Due to significant calculation errors at the external borders, the results of calculations in the range 0°–55° N, 55° W – 55° E were taken into account additionally. Let us consider in more detail the calculation results using the traditional method of correlation analysis, as well as cross-wavelet analysis [14, 15].

3. Main results and discussion
3.1. Interannual Variability

Interannual and seasonal variability is typical for almost all monthly mean characteristics of jet streams and areas of turbulated zones. For further analysis, we will introduce turbulence strength category based on certain ranges of $K_{ed}$ values: weak turbulence ($3 \times 10^4 \text{ m}^2/\text{s} > K_{ed} \geq 10^4 \text{ m}^2/\text{s}$), moderated ($10^5 \text{ m}^2/\text{s} > K_{ed} \geq 3 \times 10^4 \text{ m}^2/\text{s}$), strong ($3 \times 10^5 \text{ m}^2/\text{s} > K_{ed} \geq 10^5 \text{ m}^2/\text{s}$) and very strong ($10^6 \text{ m}^2/\text{s} > K_{ed} \geq 3 \times 10^5 \text{ m}^2/\text{s}$). Generalized information about the change in the main monthly average characteristics of the JS and the areas of turbulence zones for the period 2007-2018 presented in the table.

| Characteristic of jet streams or turbulence | Relative change,% |
|-------------------------------------------|-------------------|
| Wind speed gradient on the cyclonic side ($G_p$) | -12               |
| JS area ($S$)                              | 23                |
| JS effective width ($D_e$)                 | 24                |
| JS maximum wind speed ($V_m$)              | 2                 |
| Area of weak turbulence                    | 132               |
| Area of moderate turbulence                | 56                |
| Area of strong turbulence                  | -6                |
| Area of very strong turbulence             | -33               |

Characteristics for which the linear trend is significant with probability of 95% and higher are indicated in bold. From the data given in the table it follows that for the period 2007-2018 there was a significant increase in areas of weak and moderate turbulence, as well as a decrease in areas of strong and very strong turbulence. During the observation period, the velocity gradient of the JS from the side of the pole ($G_p$) decreased by 12%, and the effective width of the JS increased by 24%. Note that the average position of the center of the jet streams practically did not change along the latitude.

We will analyze the nature of turbulence in the above three selected areas. Figure 1 shows the distribution of average area values in these regions according to the ranges of change of $K_{ed}$ characterizing weak, moderate, strong and very strong turbulence. The area values are presented in a dimensionless form, normalized at sizes of the areas visible from the satellite. The largest area in each region is moderate turbulence (approximately 30%), followed by strong (~15%), weak (5% - 10%), and very strong (~3%) turbulence. The largest areas with strong (17%) and very strong (4%) turbulence are observed in the C region ($30^0$ E - $55^0$ E).

3.2. Relationship between turbulence zone areas and JS characteristics

The relationship of turbulated area variability with JS characteristics has been considered based on cross-wavelet analysis [14, 15]. First of all, it should be noted that JS annual and semi-annual oscillations are clearly manifested for all characteristics at the level 95%. For some characteristics, quasi-biennial and quasithree years oscillations occur [16]. The areas of turbulated zones are also characterized by a significant annual and the weaker semi-annual oscillations. The results of the cross-wavelet analysis of the temporal variation of turbulated areas and the JS characteristics showed that most correlations occur between the velocity gradient $G_p$ and the latitudinal position of the center of the jet flux $\phi$. 
As an example, Figure 2 shows the results of a cross-wavelet analysis of the series of the maximum gradient of the horizontal wind speed on the cyclonic side ($G_p$) and the latitude of the center of the jet stream ($\phi$) with the area of zones of strong turbulence in the entire considered region. 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 $\phi$) outstrip variations of areas of turbulence zones by $90^\circ$ (i.e. on a quarter of the period); upwards, they are behind by $90^\circ$. 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%.

Figure 2. Results of a cross-wavelet analysis of the $G_p$ series and the area of the zones of strong turbulence (a), $\phi$ 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.
A characteristic feature of the waveletograms in Figures 2a and 2b is in phase oscillations with a period of 12 months for $G_p$ and the area of the turbulence zones and the antiphase oscillations of $\varphi$.

In other words increasing JS velocity gradient leads to increase of area of turbulence zones, which is quite natural, and displacement of jet stream position along latitude to pole causes decrease of area of turbulence zones.

3.3. Relationship with temperature of the upper troposphere

In [17] we have considered the connections of spatial-temporal variability of high-altitude JS with essential parameters of the Earth’s climatic system - troposphere temperature ($T$), sea ice area and large-scale atmospheric phenomena. Let us focus briefly on the identified basic patterns. The greatest connection of $T$ at the levels from 200 hPa to 500 hPa can be seen with the area $S$ of jet streams and the latitude position $\varphi$ of its center. At the same time interannual variations $T$ and $S$ occur in antiphase, while $T$ and $\varphi$ in phase, i.e. with increasing troposphere temperature, the jet stream area decreases and its center shifts to higher latitudes.

A cross-wavelet analysis of the area of strong turbulence with a tropospheric temperature at 300 hPa and temperature difference between low and high latitudes at 500 hPa is presented in Figure 3. At all levels from 200 to 500 hPa, annual variations in temperature and areas with strong turbulence in the latitudinal zone from 40 to 60 degrees occur in antiphase. A similar picture is typical for very strong turbulence. In phase annual variations of areas of strong and very strong turbulence with temperature differences between low and high latitudes at levels of 200 and 500 hPa are also clearly identified. These results are easily explained given the association of turbulence zones with JS characteristics described above (see Figure 2). Therefore, the effect of temperature on the area of turbulence zones is, in our opinion, indirectly manifested through the characteristics of JS, primarily through the velocity gradient ($G_p$) and the area of JS ($S$).

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 ($0^\circ$) and high ($80^\circ$) latitudes at 500 hPa (b).

3.4. Relationships with sea-ice area and large-scale atmospheric phenomena

The greatest significant relationship between the interannual variations of sea ice area ($S_{ice}$) is observed with area $S$ (correlation coefficient 0.55) and the latitude $\varphi$ of the center of JS (correlation coefficient minus 0.69). At the same time variations of annual oscillation of $S_{ice}$ and $S$ occur mainly in phase. The $S_{ice}$ and $\varphi$ oscillations are close to antiphase. An interesting feature of the annual variations of the $S_{ice}$ and $S$ series is that the $S$ variations outstrip the $S_{ice}$ variations by about 1.5 - 2.5 months [17].

There is a general tendency towards in phase annual variations of the North Atlantic Oscillation Index (NAO) with variations of $S$ and antiphase with annual variations of $\varphi$. The patterns noted above lead to the conclusion that positive NAO values associated with an increase in pressure above normal over the central North Atlantic and a decrease over the high latitudes of the Atlantic
lead to a shift in the latitude of the centers of jet streams in a southerly direction. At the same time, two time periods are allocated in 2010 and 2013, when this trend breaks or weakens.

3.5. Short-period oscillations of jet stream characteristics
Spectral and wavelet analysis of the time series of jet streams characteristics reveals along with annual and quasi-biennial oscillations also variations with periods of less than 50 days. They are characterized by a pulsating nature, in which the bursts of vibration amplitudes alternate with the gaps at which the vibrations persist, but their amplitude decreases. Figure 4 shows the waveletograms of time series of average daily values of area and maximum speed of jet streams. All characteristics of JS are characterized by an oscillations amplitude increase in the period range of 10-40 days, especially pronounced in 2017-2019. From our point of view, oscillations with periods 10-40 days can be interpreted as a manifestation of Rossby waves. Analysis of the influence of planetary waves on jet streams and abnormal weather events is found in [18].

![Waveletograms of time series of daily average values of area (a) and maximum speed (b) of jet streams.](image)

Figure 4. Waveletograms of time series of daily average values of area (a) and maximum speed (b) of jet streams.

4. Conclusion
The method used for processing atmospheric sounding data from geostationary meteorological satellites in the absorption band of water vapor centered at 6.2 μm makes it possible to identify the regions of jet streams in the upper troposphere and the associated turbulence zones of different intensities and to analyze their spatio-temporal variability at different time scales. The results of the analysis of the relationship between the characteristics of jet streams and turbulence zones with the troposphere temperature, sea ice area, and large-scale atmospheric phenomena allow us to draw the following conclusions.

1. For most of the characteristics of jet streams and the area of turbulent zones, a noticeable change in the time interval of 2007-2018 is characteristic. The greatest changes were noted for the areas of zones occupied by weak turbulence (more than 2 times increase) and moderate turbulence (more than 50% increase).
2. There is a close relationship between the characteristics of jet streams and the areas of turbulent zones with the temperature of the upper troposphere. In this case, the effect of temperature on the area of turbulent zones manifests itself indirectly through the characteristics of jet streams.
3. A significant association of variations in the average area of stream flows and the latitudinal position of its center with the sea ice area is noted. Variations of annual oscillation of $S_{\phi}$ and $S$ occur mainly in phase. The $S_{\phi}$ and $\phi$ oscillations are close to antiphase.
4. The relationship between temporal variations in the characteristics of jet streams and large-scale atmospheric phenomena is revealed.
5. Along with annual and quasi-biennial oscillations, short-period oscillations are observed with periods 10–40 days, which can be interpreted as a manifestation of Rossby waves.

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