

Article

Analysis of the Relationship between Upper-Level Aircraft Turbulence and the East Asian Westerly Jet Stream

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Abstract: The jet stream is a primary factor contributing to turbulence, especially for upper-level aircraft. This study utilized pilot reports and ERA5 data from 2023 to investigate the relationship between upper-level turbulence and the East Asian westerly jet (EAJ). The results indicate that approximately 45.9% of upper-level aircraft turbulence occurs within the jet stream, with the lowest proportion in August and the highest in January. Additionally, the strongest vertical wind shear (VMS) is found concentrated in the lower part of the jet stream core, particularly in the South–Down part of the jet stream, where upper-level aircraft turbulence occurs most frequently (27.1%). The most turbulent area is located between 30–40° N and 110–120° E, with the main air routes experiencing turbulence being the Henan sections of G212 and B208. From a seasonal perspective, there is less frequent occurrence of upper-level aircraft turbulence in summer and autumn but more in winter and spring. The EAJ volume increases with the strengthening of the jet core wind speed, with the jet core regions being most distinct at altitudes of 200–300 hPa. Meanwhile, the jet stream intensity index peaks at 70.6 m/s in January and reaches its lowest value of 7.1 m/s in August. The jet stream axis shifts southward in winter and northward in summer, reaching the southernmost position in December at 32.2° N and the northernmost position in August at 43.5° N. Furthermore, the VMS at turbulence points within the jet stream is higher than that at the turbulence points outside the jet stream, and the Richardson number (RI) is lower. Moreover, the temporal distribution of upper-level aircraft turbulence is primarily determined by the location and intensity of the jet stream, of which the jet stream intensity index provides guidance and thus serves as a reliable indicator.

Keywords: East Asian westerly jet; clear air turbulence; spatiotemporal distribution; three-dimensional tubular structure



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1. Introduction

Turbulence is one of the crucial factors affecting civil aviation flight safety [1]. According to National Transportation Safety Board (NTSB) statistics, turbulence-induced accidents account for over 70% of all weather-related accidents [2,3]. Convectively induced turbulence (CIT) [4–6], lower-level jet turbulence (LLT) [7], mountain wave turbulence (MWT) [8,9], clear-air turbulence (CAT) [10,11], and the turbulence generated by aircraft wake vortices [12] are the main sources of aircraft turbulence [13].

Turbulence is more frequently found to occur in the vicinity of jet streams and upper-level fronts, near the tropopause, over mountainous regions, and in or near clouds, especially convective clouds [13,14]. Analyzing vertical profiles, the main areas of atmospheric turbulence are primarily distributed in the atmospheric boundary layer and within the height range of 10–12 km [15]. Some aircraft turbulence is largely avoidable because it occurs in well-defined locations, such as in the cases of CIT occurring within the vicinity of

convective storms and MWT occurring over mountain ranges [16]. However, CAT cannot be avoided by using satellites and on-board radar to detect and circumvent clouds, and it is also difficult to predict using the current numerical weather prediction models [16–18]. CAT usually occurs in the lower stratosphere and the upper troposphere within cloud-free areas or in stratiform clouds [19]. It is generally associated with large-scale waves, jet streams, upper-level fronts, and tropopause folds [14,20]. Of the various types of turbulence, CAT has the most noticeable impact on flight safety, earning it the moniker the “invisible killer” due to its substantial threat and potential for in-flight injuries [21,22]. Moreover, the jet stream is the most noticeable cause of CAT. As is well known, the strong vertical wind shear (VWS) associated with jet streams can generate Kelvin–Helmholtz instabilities, which could ultimately result in CAT [16,23–25]. Furthermore, evidence was found of a 15% increase in VMS strength to 250 hPa over the North Atlantic [23]. The occurrence frequency of CAT potential shows clear increasing trends in East Asia [3,19,24], the North Atlantic, and continental USA [16] and is expected to significantly increase in the future [17,26,27].

The East Asian westerly jet (EAJ) is a narrow and strong westerly belt characterized by large horizontal and VMS over East Asia in the upper troposphere and lower stratosphere [28]. The spatiotemporal distribution of the EAJ is well correlated with the aircraft turbulence potential, with spatial (temporal) correlation coefficients exceeding 0.75 (0.54) [3]. In addition, a long-term increasing trend in moderate-or-greater-level CAT potential has been observed over East Asia from 1979 to 2019 [29]. Meanwhile, using high-resolution sounding data, Lv et al. found a double-peak mode specific to the profiles of clear-air mean turbulence dissipation rate (ϵ) at mid-latitudes north of 30° N in winter: one at altitudes of 15–18 km and the other at altitudes of 5–8 km. The strong shear instabilities around the EAJ could account for the vertical bimodal structure [30]. The EAJ exhibits robust seasonal evolution in both intensity and location [28], leading to the north–south movement of the high-frequency turbulence region [3].

Jet streams are not continuous but instead are fragmented, meandering, and exhibit notable variations in wind speed and elevation [31]. As such, clearly identifying jet stream boundaries at a given time can be difficult and ambiguous [32]. To overcome this problem, some researchers define the jet stream as regions of wind speed stronger than 30 m/s [28,32] while others use integrated quantities [31]. The intensity of jet streams is generally characterized by the average latitudinal wind speed within a specific area [33], whereas the position of the jet stream axis is determined by the latitude at which the maximum wind speed occurs [28].

According to previous research, the spatiotemporal distribution characteristics of upper-level turbulence are significantly affected by jet streams. However, diagnostic indices are often used to determine the regions of turbulence potential and their changes. Meanwhile, the EAJ is an irregular tubular structure in three-dimensional space, with thin ends and a thick middle [34]. Its three-dimensional structure will determine its influence on upper-level aircraft turbulence. Based on this, this article begins by examining the spatial evolution characteristics of the EAJ and analyzing its temporal distribution. At the same time, VMS in the jet stream is calculated for regions of potential turbulence. Next, observed turbulence events (pilot reports, PIREPs) are used to analyze the spatiotemporal distribution patterns of upper-level aircraft turbulence (above 6000 m). Finally, the location, intensity, VMS, Richardson number (RI), and other factors of the EAJ and their relationship to the pattern of upper-level aircraft turbulence distribution are further analyzed.

2. Materials and Methods

The research area covers altitudes from over 6000 m to the highest flight level in China (Figure 1). The datasets used in this study are the PIREPs, ERA5, Aeronautical Information Publication (AIP), and National Aeronautical Information Publication (NAIP).

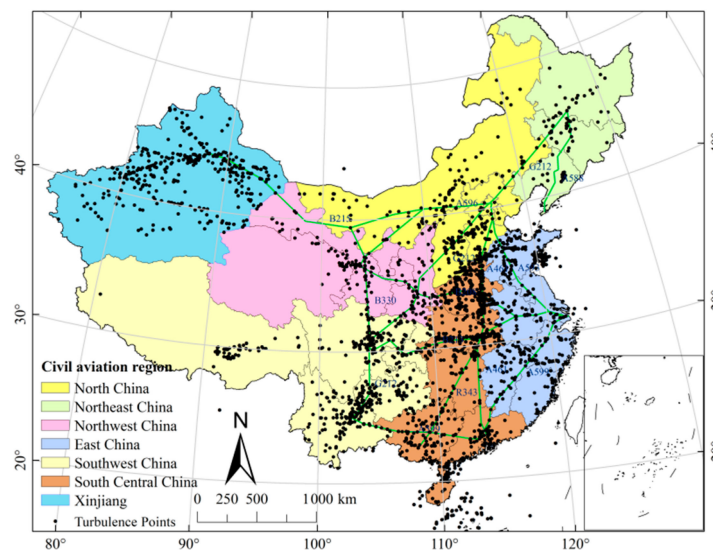


Figure 1. Research region and distribution of PIREPs. The blank dots represent points of aircraft turbulence while the green solid lines indicate the main air routes in China. The background colors correspond to the seven major regions of civil aviation in China.

2.1. Pilot Reports

PIREPs are proactive reports submitted to controllers, primarily via regular voice radio contact, when weather hazardous to aviation is encountered during aircraft operation. After being received, the message is forwarded by the controller to the Aviation Meteorological Center, which then disseminates it to the public through fax or data systems and records it in their database. PIREPs serve as an important supplement to the current observation methods in civil aviation, providing other aircraft with timely information for detecting and avoiding dangerous weather. They include information such as the location, aircraft type, and turbulence (and/or icing, low-level wind shear) height and intensity (light (LGT), moderate (MOD), severe (SEV)). Additionally, details of weather conditions such as jet streams, wind shear, mountain waves, convection, and upper-level troughs are reported.

In 2023, there were a total of 6671 PIREPs related to turbulence in China. Quality control measures were applied, such as removing duplicates and discarding PIREPs that lack location information or have unclear location data. Finally, a total of 3916 PIREPs that occurred above 6000 m were used to study the relationship between upper-level aircraft turbulence and the jet stream. The distribution of these PIREPs and the main route are shown in Figure 1, where 96.8% correspond to moderate and severe turbulence, as there is no mandatory requirement to report LGT. Therefore, in the analysis below, no distinction is made with respect to the intensity of turbulence.

As pointed out by Schwartz, inaccuracies in position, time, and intensity in PIREPs can introduce some uncertainty into the results and should be examined before investigating turbulence statistics. Sharman (2006) evaluated the uncertainties in position and time in PIREPs and found that the median uncertainty was approximately 50 km horizontally, 200 s in time, and 70 m vertically [35]. These time and position differences fall within the windows typically used for analyzing the relationship between turbulence and jet streams. The horizontal position uncertainty of 50 km corresponds to about two ERA5 grid points, and since the turbulence fields are relatively smooth both horizontally and vertically, this uncertainty should have a negligible effect on the results. Additionally, intensity uncertainties in PIREPs are considered acceptable due to the high proportion of moderate and severe turbulence reports.

Since PIREPs from Chinese aircraft are textual data, and descriptive statements for navigation points are used for the location of turbulence, it is necessary to preprocess the data and convert them into specific latitude and longitude grid points. The method

for determining latitude and longitude involves using AIP or NAIP data to identify the origin of the described location. Subsequently, the spherical distance formula is used to calculate the direction and distance, and the latitude and longitude values of the points of the shaking are finally obtained, with data precise to two decimal places. The background circulation field resulting in aircraft turbulence often affects a large area; therefore, it is rational to conclude that this substitution does not significantly affect the study of aircraft turbulence.

The altitude of aircraft turbulence is determined as barometric altitude, which is measured in meters. In order to match the ERA5 data, the units need to be converted to hPa. This article uses the following barometric formula for conversion:

$$z_1 - z_0 = -\frac{R_d T}{g} \ln \frac{P_1}{P_0} \quad (1)$$

where z_1 is the turbulence height, z_0 is the standard sea level height of 0 m, and R_d and g are constants, 0.287 J/(g °C) and 980.6 cm/s, respectively. T is the average absolute temperature of the gas layer, in K, which can be calculated from the standard atmosphere. P_1 is the pressure corresponding to the turbulence height and P_0 is the standard atmospheric pressure of 1013.25 hPa. Given the height of the turbulence, the corresponding air pressure can be calculated.

2.2. ERA5 Reanalysis Data

ERA5 is the fifth-generation atmospheric reanalysis dataset produced by the ECMWF (European Centre for Medium Range Weather Forecasts) for global climate and weather from 1940 to the present, providing hourly estimates of a large number of atmospheric, wave, and land surface variables. The data have a horizontal resolution of $0.25^\circ \times 0.25^\circ$ and a time resolution of 1 h, and include 37 vertical layers from 1 hPa to 1000 hPa on the isobaric surface, covering the global horizontal range.

This article analyzes the spatiotemporal distribution characteristics of the EAJ in 2023 on a monthly basis using hourly data at a spatial resolution of $0.25^\circ \times 0.25^\circ$ and a height range of 1000–100 hPa. The spatial range is 10–56° N and 72–136° E. The main elements used are vertical velocity, geopotential height, and the u and v components of horizontal wind. The data were accessed from the European Central Data Center (<https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels>) in 10 March 2024. The data format used in this article is netCDF (nc), and images were viewed and drawn using MATLAB, which supports this format.

2.3. Aeronautical Information Publication

The AIP and NAIP datasets are issued by the state or authorized by the state according to the International Civil Aviation Convention. Ensuring that such navigation data are readily accessible is essential for the safe operation of aircraft within the country, where they also serve as a fundamental source of important long-term navigation information.

2.4. Methods for Extraction of Jet Stream Features

According to the definition of high-altitude jet streams, the maximum wind speed at the center of the jet stream is greater than or equal to 30 m/s in the upper troposphere [31,34]. Based on this, areas with a wind speed greater than or equal to 30 m/s within an isobaric surface height of 400–100 hPa are considered high-altitude jet stream regions in this study.

Conceptually, the Eurasian jet has three components: the West Asian sector (WAJ), the East Asian component (EAJ), and the western Pacific part (WPJ) [36]. Meanwhile, the East Asian subtropical westerly jet stream (EASWJ) is an important component of the EAJ. Since this study mainly focuses on the impact of jet streams on aircraft turbulence in eastern China, the spatiotemporal characteristics of the EASWJ are analyzed. To study the spatiotemporal variation of the westerly jet stream, it is necessary to clarify the methods for calculating the average position of the jet stream axis as well as the jet stream intensity.

(1) Jet stream axis index

The jet stream axis generally refers to the meridional position of the maximum wind speed at each longitude [37]. In this study, the jet axis index proposed by Song et al. [38] is utilized to analyze the north–south movement of the EASWJ, where the average latitude of the location of the maximum westerly wind is calculated for different longitudes at 200 hPa (110~130° E, 30~50° N). The jet stream index tends to be larger (smaller) when the SWJ is northward (southward).

(2) Jet stream intensity index

The intensity of jet streams is generally represented by the zonal wind within a specific area [39]. According to previous studies [40], the jet stream intensity index is defined as the 200 hPa average U wind speed in the key area (110~130° E, 30~37.5° N). When the jet stream intensity index is high (low), the subtropical westerly jet stream tends to be strong (weak).

2.5. Kernel Density Estimation

Kernel density estimation is a non-parametric method for estimating the surface density of two types of data—points and lines—within their surrounding domain. The probability density function of the data is estimated using a set of sample data [41]. This method is commonly used in research fields such as geographic information systems, urban planning, and ecology, aiding in understanding data distributions and enabling more informed and effective decision making [41].

PIREP data are discrete single-point data. To better study the spatial distribution characteristics of flight turbulence throughout the entire China region, the kernel density analysis function of ArcGIS 10.8 software was used to process the PIREP data with latitude and longitude information after data quality control, enabling the spatial distribution characteristics of aircraft turbulence to be determined. Simultaneously, using AIP data, the nuclear density distribution of aircraft turbulence was spatially overlaid onto China's main air routes to examine the spatial distribution characteristics of aircraft turbulence along the air routes.

3. Spatiotemporal Distribution Pattern of the Jet Stream

3.1. Structural Characteristics of the Jet Stream Tube

The three-dimensional structure map of the hourly horizontal wind speed at the 1000~100 hPa level of the EAJ in 2023 was plotted, which helps to intuitively understand the spatial morphology and temporal evolution characteristics of the subtropical jet stream. The hourly representations for winter, spring, summer, and autumn were prepared separately, and only the areas with wind speeds ≥ 30 m/s are shown in the figure (Figure 2).

From Figure 2, it can be seen that the subtropical jet stream in East Asia is not simply a belt-like system at a certain height, but rather, an irregular tubular structure of varying thickness in three-dimensional space. The volume of the jet stream tube increases with the strengthening of the jet core wind speed, and jet core regions are most prominent near the level of 200~300 hPa. The intensity and volume of the jet streams vary greatly in different seasons and are the strongest in winter. The jet stream tube occupies the upper and middle layers of the troposphere in the vertical direction and can extend downwards to around 600 hPa in winter, and the jet stream core is located over the western North Pacific. From winter to summer, the jet stream tube moves northward, with a significant decrease in intensity and a gradual reduction in volume and vertical thickness. Meanwhile, the wind speed decreases around the jet stream core, with the range of horizontal extension exceeding the vertical thickness. The latitude of the jet stream core will vary with longitude, being northward between 120 and 130° E and southward between 100 and 110° E in winter.

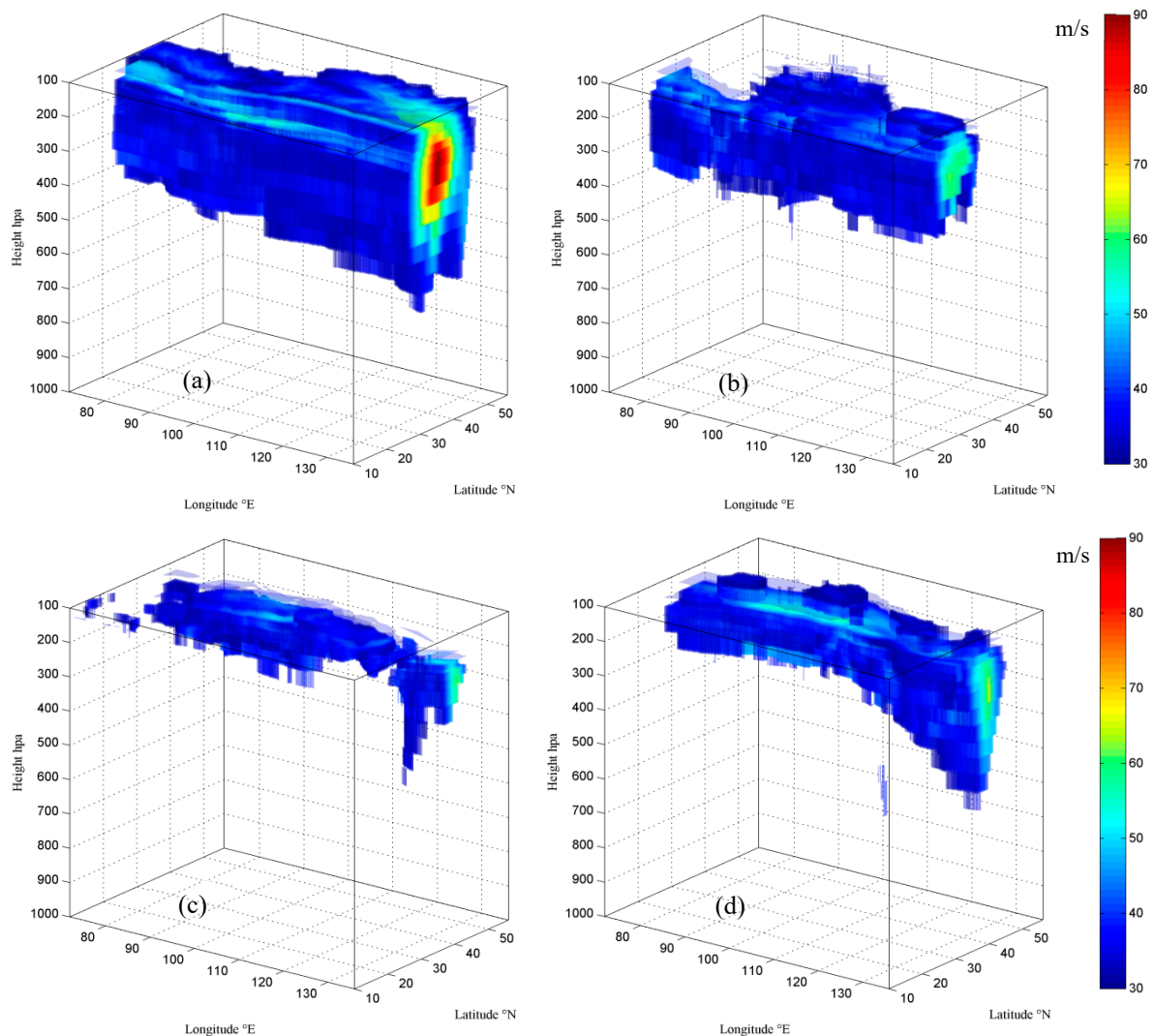


Figure 2. Three-dimensional spatial structure of the EAJ at 0 o'clock (BJT) on 1 January (a), 1 April (b), 1 July (c), and 1 December (d) in 2023.

3.2. Temporal Distribution Characteristics of the Jet Stream

The temporal distribution of the jet stream axis was analyzed using hourly ERA5 data from 2023 at 100–400 hPa. The latitudes of the points of maximum wind speed along the axis at various altitudes from 20 to 50° N were calculated, and the distribution of this axis at different altitudes and across different months was plotted. As shown in Figure 3, there is a consistent shift in the jet axis northward in summer and southward in winter across different heights. The analysis of the jet stream axis index shows that the index is largest in August at 43.5° N and smallest in December at 32.2° N (Figure 4).

The latitudes of the maximum wind speed at different levels are most concentrated in summer and most dispersed in spring. Meanwhile, the maximum wind speed varies across different latitudes and longitudes, with the amplitude of movement being slightly smaller east of 110° E and larger west of 90° E. After entering spring, the maximum wind speed axis shifts significantly northward in April at the lower level, while it only starts to move northward in May at the higher level. In spring, the Qinghai–Tibet Plateau gradually transforms from a cold source to a heat source, with an increase in temperature difference on the northern side of the plateau and a decrease on the southern side. The northern branch of the airflow is stronger than the southern branch. Compared to the upper-level winds, lower-level winds are more susceptible to the thermal effects of the underlying surface and therefore have a more northerly speed axis [42]. In July and August, the maximum wind

speed axis of each layer is located north of 40° N, remaining at approximately the same latitude. In September, the jet stream axis begins to retreat southward. Due to the blocking effect of the plateau terrain on lower-level winds, the maximum wind speed axis is further north than that of the upper levels. In December, the jet stream tube moves southward to its winter position. Meanwhile, the jet stream intensity index is highest at 70.6 m/s in January and lowest at 7.1 m/s in August.

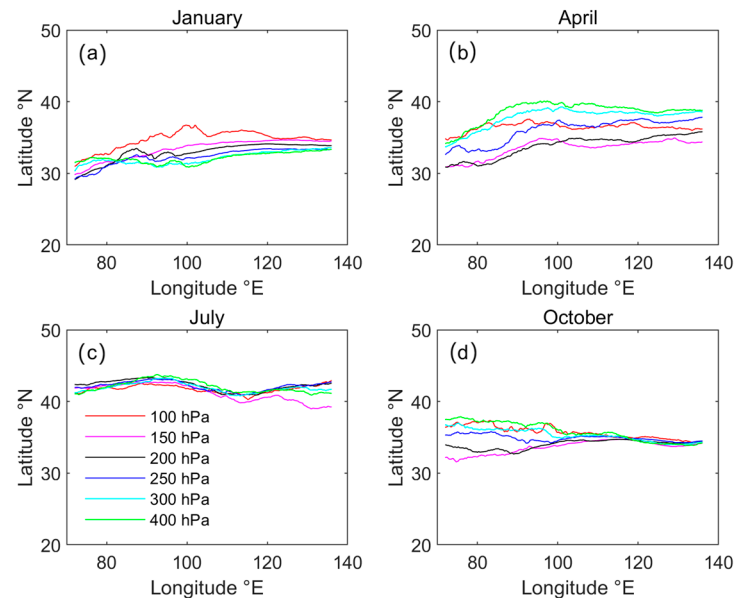


Figure 3. Average position of maximum wind speed axis at 400–100 hPa, calculated using ERA5 hourly data. (a) January, (b) April, (c) July, (d) October.

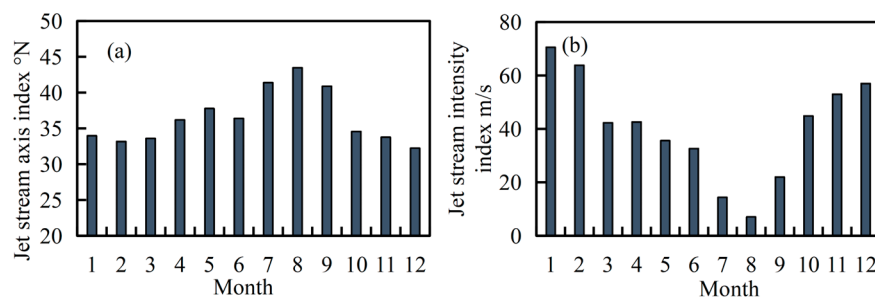


Figure 4. Monthly characteristics of jet stream axis index (a) and jet stream intensity index (b) in 2023, calculated using ERA5 hourly data according to the methods in Section 2.

The temporal distribution characteristics of the jet intensity index and the jet axis index are exactly opposite (Figure 4), with the jet stream axis index at its maximum when the jet stream intensity index is at its minimum, and vice versa. The correlation coefficient between them is as low as -0.92 , indicating a highly significant inverse correlation. Further analysis shows that the correlation coefficients between the corresponding daily and hourly results are -0.75 and -0.73 , respectively, both of which passed the significance test. The above results indicate a consistent relationship between the intensity and location of the jet stream: the stronger the intensity of the jet stream, the more southerly its location; the weaker the intensity, the more northerly its location. This result is consistent with previous research conclusions [34,36,42].

3.3. VMS in the Jet Stream

VMS strength in jet streams is an important factor causing aircraft turbulence [16]. Due to the irregular long tube structure of the subtropical jet stream, its VMS is not uniform

throughout. To analyze the horizontal wind speed and VWS at different positions within the jet stream, ERA5 hourly data were utilized to calculate the VWS along the meridian of 120° E. As seen in Figure 5, there are significant differences in the horizontal wind speed and VWS of the jet stream across different seasons. In January, the horizontal wind speed of the jet stream reaches a maximum, with core maximum wind speeds exceeding 80 m/s . In August, the horizontal wind speed is the lowest, with wind speeds below 30 m/s at 120° E (Figure 5).

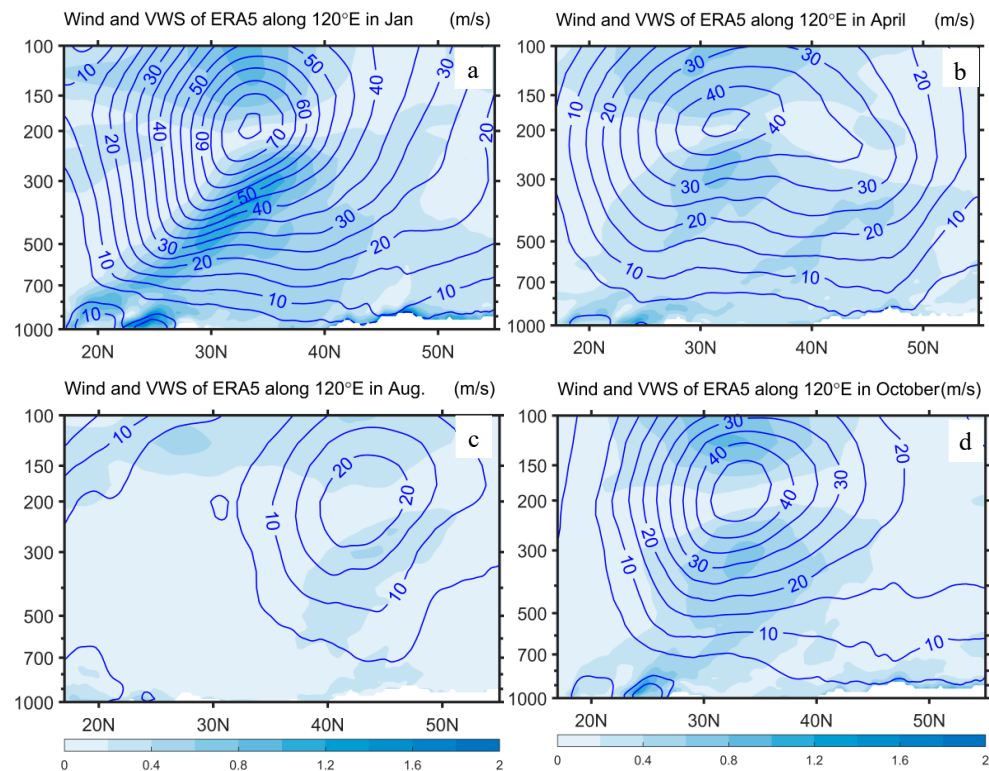


Figure 5. Average horizontal wind speed (curve, unit: m/s) and VWS (color represents horizontal wind vertical shear intensity, unit: $(\text{m/s})/100\text{ m}$) profiles in January (a), April (b), August (c), and October (d).

The seasonal distribution characteristics of VWS are similar to those of horizontal wind speed, with the strongest VWS in January and the weakest in August. Furthermore, VWS is found to be stronger in the vertical direction and weaker in the horizontal direction and near the jet stream core. The main area of high VWS is distributed in the lower part of the jet stream core and extends southward as the altitude decreases, causing more variation in VWS on the south side of the lower part.

In January, the high-VWS zone is located within the range of $300\text{--}500\text{ hPa}$ in the vertical direction and $30\text{--}35^{\circ}$ N in the horizontal direction. This zone becomes less prominent and shifts higher vertically while showing little change horizontally from winter to spring. After June, its horizontal position rapidly shifts northward, reaching its northernmost point in August, and then gradually shifts southward.

4. Spatiotemporal Distribution Pattern of PIREPs

4.1. Spatial Distribution of PIREPs

The vertical distribution characteristics of aircraft turbulence were statistically analyzed using height information from PIREPs at 500 m vertical intervals. As shown in Figure 6, the altitude of aircraft turbulence occurrence ranges from 0 m to $14,000\text{ m}$, and the frequency of occurrence varies across different altitudes, being primarily concentrated in the range of 3500 m to $10,500\text{ m}$ and accounting for up to 84.9% of turbulence events. This vertical distribution pattern is related to the proportion of flight time in each flight

phase, with higher frequencies of turbulence corresponding to longer cruising periods. The aircraft turbulence above 6000 m is closely related to high-altitude jet streams, accounting for 59.5% of the total turbulence frequency, which is the focus of this study.

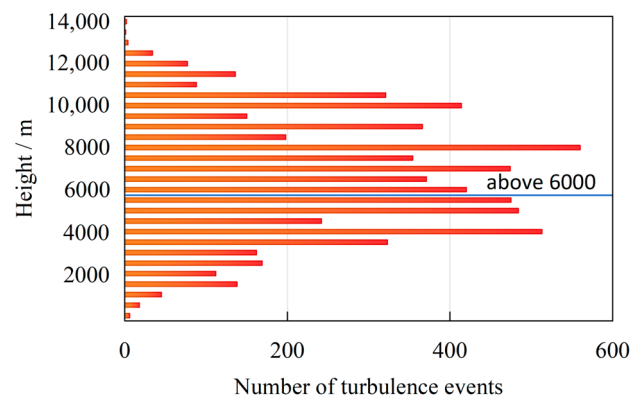


Figure 6. Vertical distribution of aircraft turbulence. The number of PIREPs per 500 m altitude was calculated for 2023.

The overall trend of upper-level aircraft turbulence in China shows more turbulence in the east and less in the west, with higher frequencies of turbulence in the central region and lower frequencies around the periphery. The distribution characteristics of turbulence along China's air routes are evident. With the exception of Xinjiang, the western regions have less turbulence due to fewer air routes. The high-value areas of turbulence events are generally distributed in the air route area. The most turbulent area is located between 30–40° N and 110–120° E, with the main air routes of turbulence being the Henan sections of G212 and B208 (Figure 7).

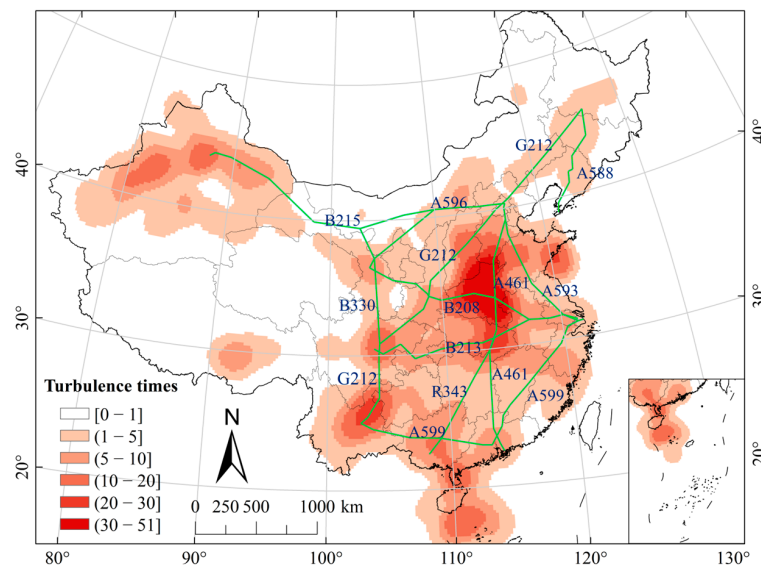


Figure 7. Kernel density estimation of aircraft turbulence above 6000 m in China in 2023. The color code is the number of turbulence events, and the green lines are the main air routes in China.

From the perspective of various regions in China, Northeast China has the lowest occurrence of aircraft turbulence, whereas South Central China has the most, followed by Southwest China and Xinjiang province (Figure 8). Due to significant differences in flight volume between the different regions, the occurrences of turbulence for individual flights were calculated. East China has the highest number of flights nationwide, while Xinjiang province has the fewest. Meanwhile, the flight volume in South Central China greatly exceeds that in Xinjiang province. In terms of the number of turbulence events per

million flights, Xinjiang province has the most, followed by South Central China. This may be related to the complex terrain and high mountains in Xinjiang.

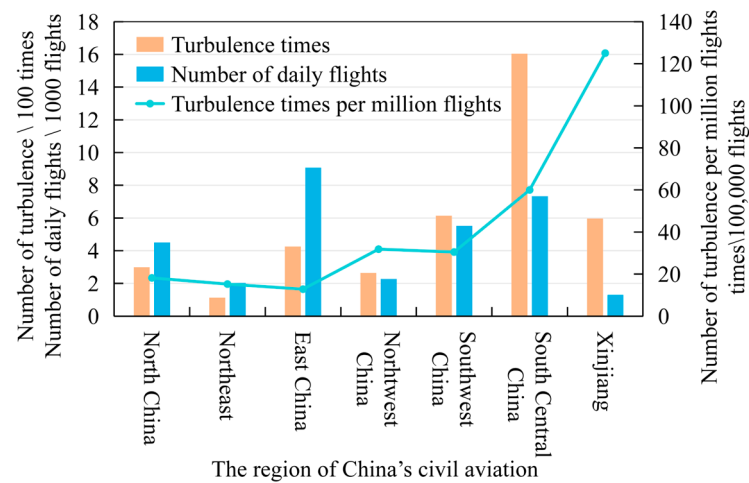


Figure 8. Distribution of aircraft turbulence in China's civil aviation region. The orange bar represents the number of aircraft turbulence events, the blue bar represents the daily average flight volume in the region, and the blue line represents the number of turbulence events per million flights.

The spatial distribution characteristics of aircraft turbulence in different seasons are generally similar, with more turbulence occurring in South Central China and less in Northeast and East China (Figure 9). However, there is a notable difference in Yunnan during spring, where turbulence is more frequent due to the seasonal strong winds.

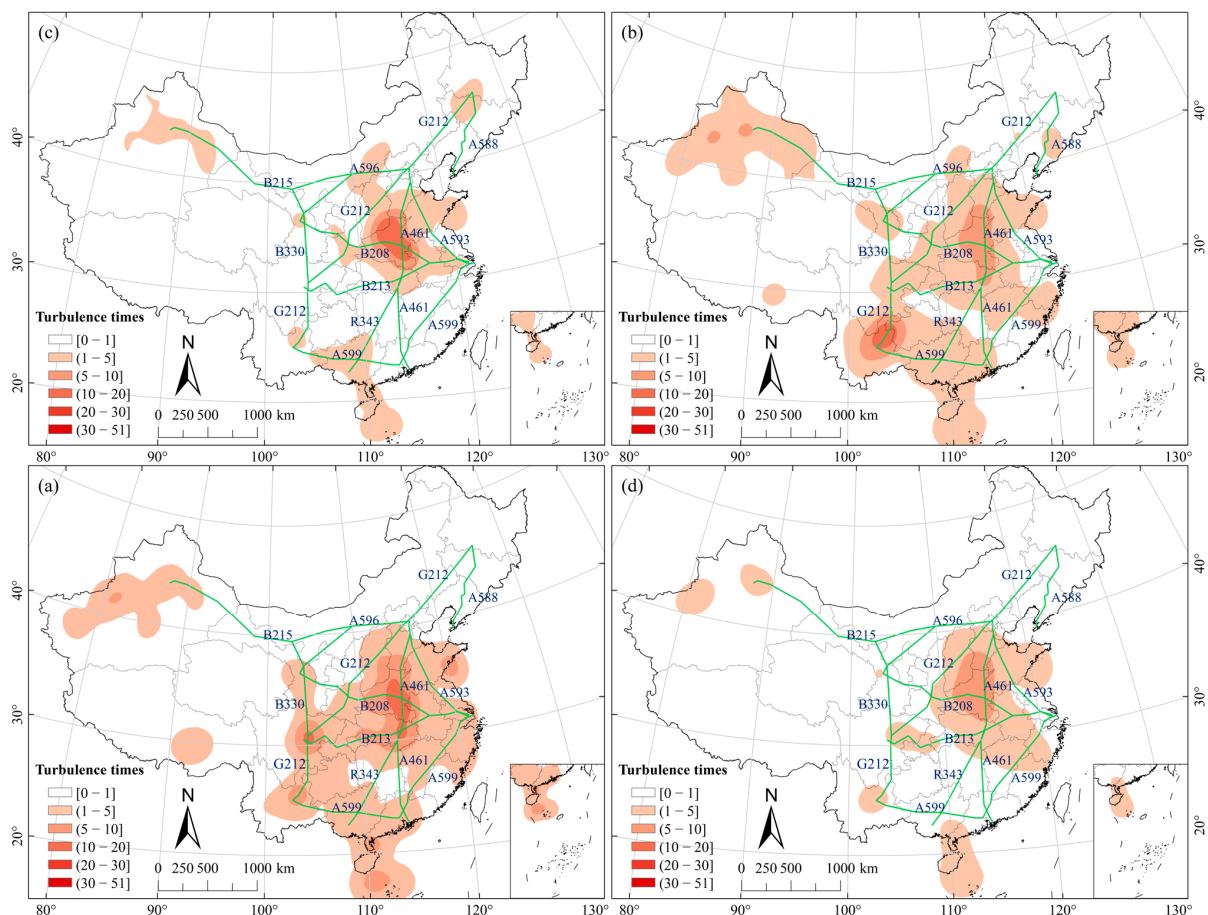


Figure 9. Similar to Figure 8, but for DJF (a), MAM (b), JJA (c), and SON (d).

4.2. Temporal Distribution of PIREPs

To reveal the temporal behavior of aircraft turbulence, a multi-temporal statistical analysis was conducted on PIREPs. As shown in Figure 10a, the number of turbulence events occurring within 8760 h in 2023 was counted. There was a total of 6197 h without any PIREPs and 1696 h with only one PIREP, and the maximum number of PIREPs within an hour is seven, which is relatively low considering the large number of flights. Additionally, regarding the number of PIREPs per day, 80% of the daily reports correspond to fewer than 16, with none exceeding 42 (Figure 10b).

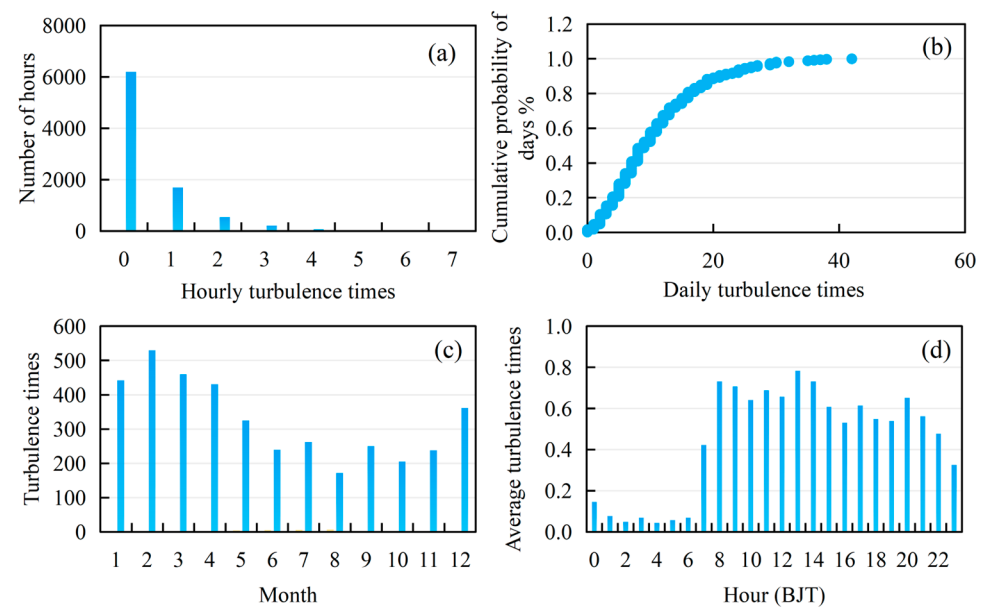


Figure 10. Multi-temporal statistical analysis of PIREPs for the (a) number distribution of hourly turbulence times; (b) cumulative probability distribution of daily turbulence times; (c) monthly turbulence occurrences; and (d) average hourly turbulence times for every hour of the day.

Figure 10c shows the number of aircraft turbulence events per month in 2023. February had the highest number of aircraft turbulence events while July had the lowest. From a seasonal perspective, there were fewer reports of aircraft turbulence in summer and autumn and more in winter and spring. The main reason for this result is that there are fewer turbulence events caused by convection in pilot reports while there are more turbulence events caused by jet streams [19]. Moreover, it can be seen that the number of aircraft turbulence events was exceptionally low from 00:00 to 6:00 (BJT) but high from 7:00 to 24:00. The number of aircraft turbulence events peaks at 13:00. This may be related to the duration of the flights over China, which is extremely low before dawn. As the number of flights changes, the number of aircraft turbulence events also varies correspondingly (Figure 10d).

5. Relationship between Aircraft Turbulence and Jet Streams

5.1. Spatial Distribution Correlation

The aim was to determine the spatial correlation between upper-level jet streams and aircraft turbulence, calculate the proportion of turbulence within the jet stream range, and analyze the regions where turbulence occurs within the three-dimensional structure of the jet stream as well as according to the meteorological conditions at that location. First, based on the location of the turbulence and the jet stream range, it was determined whether the turbulence was within the jet stream area. Next, based on the position of the jet stream axis, the jet stream was divided into four regions: North–Down (ND), North–Up (NU), South–Up (SU), and South–Down (SD) (Figure 11). Finally, the number of aircraft

turbulence events in each jet stream region was counted, and meteorological parameters such as VMS and vertical velocity at the turbulence location were calculated.

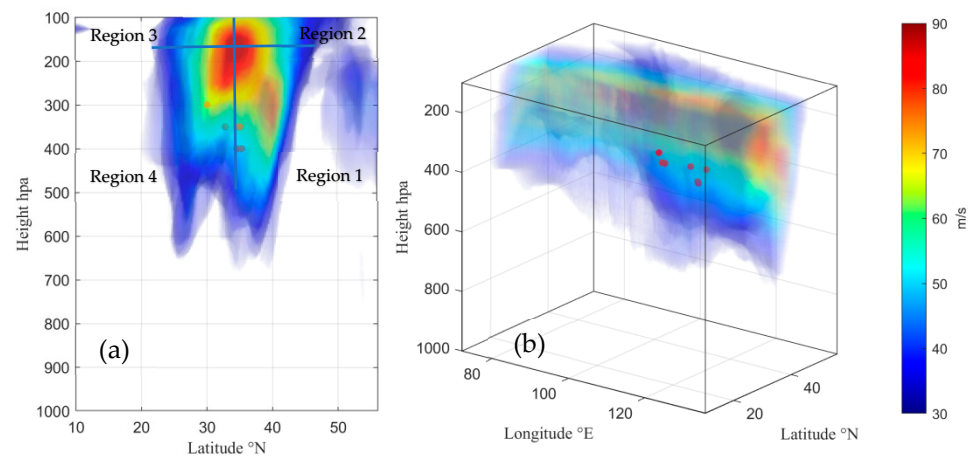


Figure 11. Distribution of high-altitude jet streams and turbulence points at 10:00 on 26 January (BJT), 2023, corresponding to the time of most frequent aircraft turbulence. The color bar indicated in the color zone represents the wind speed, which is ≥ 30 m/s. The red dots represent turbulence points from PIREPs. (a) is a two-dimensional perspective; (b) is a three-dimensional perspective.

The data presented in Table 1 reveal that the proportion of turbulence points within the jet stream was 45.9% throughout the year, with August having the lowest proportion and January the highest. The frequency of aircraft turbulence varies in different regions of the jet stream, with more turbulence occurring below the jet stream axis than above, and more in the south than in the north, with the highest frequency of turbulence occurring within region 4 (Figure 11). The main reason for the higher number of turbulence events below the jet stream compared to above is believed to be related to the number of flight altitude layers in the upper and lower parts of the jet stream, as well as the size of different parts of the jet stream. In particular, the upper part of the jet stream accommodates 6 flight levels, whereas the lower part encompasses 19. Additionally, the area beneath the jet stream axis constitutes 54.7% of the jet stream's total range.

Table 1. The relationship between the location of turbulence points and the EAJ.

Month		1	2	3	4	5	6	7	8	9	10	11	12	Year
Turbulence times		442	530	460	431	325	240	262	172	250	205	238	361	3916
The proportion of	Inside of EAJ	67.4	62.8	57.2	49.7	33.8	15.4	16.4	11	17.2	37.1	51.7	65.7	45.9
turbulence events (%)	Outside of EAJ	32.6	37.2	42.8	50.3	66.2	84.6	83.6	89	82.8	62.9	48.3	34.3	54.1
Turbulence points in ND region		106	116	47	105	46	10	19	10	19	18	65	98	659
Turbulence points in NU region		1	0	5	7	4	2	0	0	0	0	1	1	21
Turbulence points in SU region		3	5	14	11	7	0	1	0	2	1	4	6	54
Turbulence points in SD region		188	212	197	91	53	25	23	9	22	57	53	132	1062
Mean horizontal wind at	Inside of EAJ	45.7	41.9	40.4	39.5	39.8	40.2	39.6	40.5	36.8	37.4	40.4	41.8	41.4
turbulence sites (m/s)	Outside of EAJ	20.6	22.3	22.4	21.0	18.1	14.5	14.6	12.6	16.3	20.4	22.3	24.2	18.8
Mean absolute value of	Inside of EAJ	0.22	0.19	0.18	0.25	0.19	0.19	0.17	0.21	0.23	0.16	0.26	0.21	0.21
vertical velocity (Pa/s)	Outside of EAJ	0.20	0.19	0.18	0.24	0.20	0.18	0.20	0.18	0.21	0.18	0.25	0.24	0.20
Mean VWS at turbulence	Inside of EAJ	1.00	0.99	0.85	0.73	1.04	0.77	0.94	0.91	0.72	0.91	0.73	0.84	0.89
sites (m/s/100 m)	Outside of EAJ	0.61	0.70	0.60	0.52	0.52	0.50	0.47	0.42	0.49	0.55	0.49	0.67	0.54
RI at turbulence sites	Inside of EAJ	2.14	2.20	2.77	3.19	2.64	2.93	2.46	4.16	4.33	2.17	3.13	2.72	2.64
	Outside of EAJ	3.48	3.73	4.83	6.33	6.45	6.66	8.35	8.16	7.33	6.79	6.86	4.29	6.14

The average horizontal wind and VWS at the location of the aircraft turbulence is higher in winter and lower in summer, while the vertical velocity did not vary significantly in 2023. Similarly, the mean horizontal wind speed at the point of upper-level aircraft turbulence (above 6000 m) in 2023 averaged 20.1 m/s. The lowest wind speed of 36.8 m/s occurred in August, and the highest of 37.5 m/s in January, reflecting the monthly distribu-

tion characteristics of upper-level wind speed. Furthermore, it was found that the average wind speed at the turbulence points within the jet stream is higher than that outside the jet stream, while the difference in vertical wind speed is not significant. Additionally, the VMS at the turbulence points within the jet stream was found to be higher than that at the turbulence points outside the jet stream, and the RI value was found to be lower. These indicate that there is a significant difference in the causes of aircraft turbulence between the inside and outside of the jet stream.

5.2. Temporal Distribution Correlation

To further analyze the correlation between the changes in aircraft turbulence position and jet stream position or intensity on a time scale, the monthly frequency of aircraft turbulence was calculated in the eastern region of China (110~130° E, 20~50° N), which is significantly influenced by jet streams. The latitude and longitude information of each turbulence point was used to determine the monthly center of gravity for turbulence locations. Subsequently, correlation analysis was conducted using the monthly jet stream intensity index and jet stream axis index, with the results presented in Figure 12.

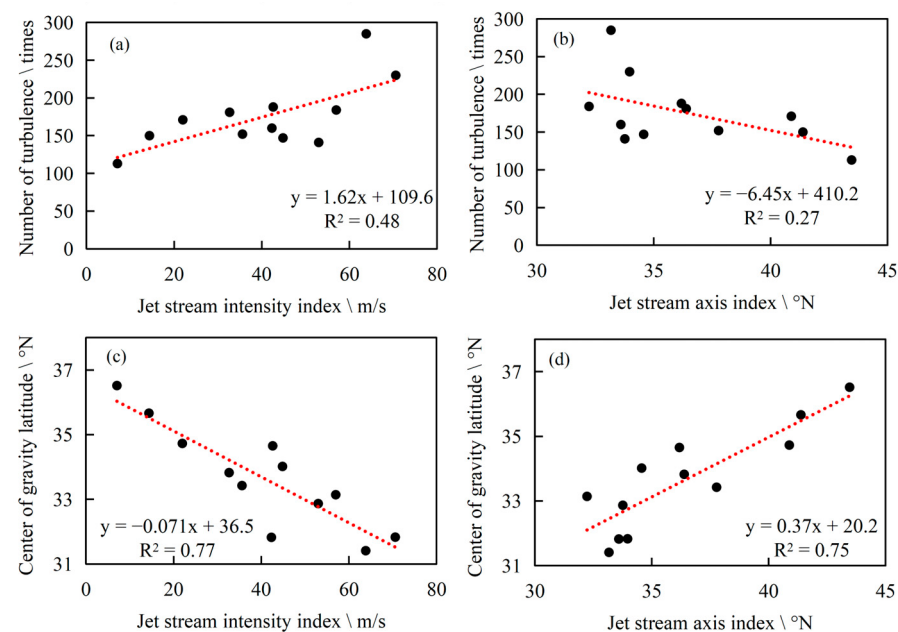


Figure 12. Correlation between (a) the jet stream intensity index and the number of turbulence events and (c) the jet stream intensity index and the latitude of the turbulence's center of gravity. Correlation between (b) the jet stream axis index and the number of turbulence events and (d) the jet stream axis index and the latitude of the turbulence's center of gravity.

In general, the temporal distribution of upper-level aircraft turbulence is mainly determined by the location and intensity of the jet stream. The jet stream intensity index is significantly positively correlated with the number of aircraft turbulence events ($p < 0.05$) and extremely significantly negatively correlated with the latitude corresponding to the center of gravity of the aircraft turbulence ($p < 0.01$). According to the linear fitting of these relationships, the former has a coefficient of determination of 0.48 (Figure 12a) while the latter has a coefficient of determination of 0.77 (Figure 12c). Similarly, the jet stream axis index is negatively correlated with the number of aircraft turbulence events and is extremely significantly positively correlated with the latitude of the aircraft turbulence's center of gravity ($p < 0.01$).

6. Conclusions and Discussion

Based on the latest generation reanalysis data ERA5 from ECMWF and 3316 PIREPs in 2023, this study analyzes the relationship between upper-level aircraft turbulence and the East Asian westerly jet (EAJ).

The volume of the jet stream tube increases with the strengthening of the jet core wind speed, and the jet core regions are most prominent near the altitudes of 200–300 hPa. The intensity and volume of jet streams vary greatly across seasons, being the strongest in winter. The north–south displacement of the jet stream axis is not uniform at each level, and the lower-level wind speed axis shifts more northerly than the high-level axis in spring and autumn, which is consistent with the findings of Yao et al. [42]. The main area of stronger VWS is distributed in the lower part of the jet stream core, particularly in the South–Down part of the jet stream.

The aircraft turbulence above 6000 m accounts for 59.5% of the total occurrences of turbulence. The most turbulent area is located between 30–40° N and 110–120° E, with the main air routes experiencing turbulence being the Henan sections of G212 and B208. Seasonally, there is less upper-level aircraft turbulence in summer and autumn and more in winter and spring. These results regarding the spatiotemporal distribution of upper-level aircraft turbulence were also obtained through the calculation of CAT diagnostics [3]. The daily distribution characteristics of upper-level turbulence are determined by the duration of the flights over China.

Approximately 45.9% of upper-level turbulence occurs in the jet stream, with the lowest proportion in August and the highest in January. Furthermore, more turbulence occurs below the jet stream axis than above, with the highest frequency of turbulence occurring within the South–Down part of the jet stream. The analysis is confined to the single year of 2023, which may not comprehensively reflect long-term trends or interannual variations in jet stream behavior and their impact on turbulence. To bolster the reliability of these findings, comparisons were made with previous studies and a thorough exploration of existing data was conducted. The proportion of turbulent events within and outside the jet stream aligns with the discoveries of Kim et al. (2011) [19], who noted that jet-stream-induced turbulence accounted for 41.2% of all turbulence events observed over South Korea. Additionally, these research outcomes mirror the proportion of jet-related turbulence reported by pilots, where such events accounted for 37.8% of the total turbulence events reported. As a result, the research findings possess a considerable degree of credibility.

At the location of aircraft turbulence, the average VWS is higher in winter and lower in summer, while the vertical velocity does not vary significantly. The temporal distribution of upper-level turbulence is mainly determined by the location and intensity of the jet stream, with the jet stream intensity index serving as a more reliable indicator. Similarly, comparable results were also found through the upper-level turbulence empirical turbulence indices and theoretical instability indicators [3,29].

This study enables a deep understanding of the spatiotemporal characteristics of the upper-level turbulence in China through pilot reports as well as consideration of the relationship with jet streams. However, there are still some limitations. PIREPs are event-based data manually reported by pilots, and the turbulence intensity tends to be determined based on the pilot's experience [19]. Turbulence observations through in situ measurements, for instance, of EDR, should be conducted for comparative analysis [43]. Meanwhile, constructing a more reliable model of the spatiotemporal relationship between upper-level turbulence and jet streams over China requires collecting PIREP data over longer periods. Furthermore, the three-dimensional structure of the jet stream also includes the inlet and outlet zones, and their impact on turbulence still needs to be analyzed in detail.

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