Distribution Characteristics of Tropopause Fold and Its Relationship with Aircraft Turbulence in the Tibetan Plateau Region

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Abstract. Tropopause Fold (TF) is a significant atmospheric phenomenon in the upper troposphere and lower stratosphere (UTLS) in mid-latitudes, with critical implications for weather, climate, and particularly aviation safety, especially over the Tibetan Plateau. This study investigates the distribution characteristics of TF and its relationship with Clear Air Turbulence (CAT) in the Tibetan Plateau region using reanalysis data and aircraft observations. Results indicate that the occurrence frequency of TF is highest in winter and lowest in summer. The spatial distribution of TF shows a zonal pattern across all seasons. In winter, high-frequency TF zones are located over the Tibetan Plateau around ~30°N, while in summer, the high-frequency zones shift southward to the southern edge of the plateau. The occurrence frequency of TF-related CAT is significantly higher in winter than in other seasons, with the affected areas primarily located west of the Hengduan Mountains. The greater the depth of the fold, the stronger the aircraft turbulence.

Keywords: Tibetan Plateau; Tropopause Fold; Clear Air Turbulence

1 Introduction

Clear-Air Turbulence (CAT) mainly occurs in the upper troposphere and lower stratosphere (UTLS), and is a leading cause of injuries to passengers and crew members during the cruising phase of commercial flights [1]. Pilots typically avoid turbulence areas by changing their course or altitude when encountering CAT, which somewhat affects airspace operation efficiency and increases the workload of air traffic controllers. Additionally, the personnel compensation and extra fuel consumption caused by unexpected CAT also impose significant economic pressure on airlines [2]. Therefore, the distribution characteristics, formation mechanisms, and forecasting techniques of clear-air turbulence have always been key areas of research in aviation meteorology [3].

W. He et al. (eds.), *Proceedings of the 2024 10th International Conference on Advances in Energy Resources and Environment Engineering (ICAESEE 2024)*, Atlantis Highlights in Engineering 36,
https://doi.org/10.2991/978-94-6463-708-3_55

The formation of CAT is closely related to Kelvin-Helmholtz instability, and the upper-level jet stream is an important source of this instability [4,5]. Strong wind shear near the jet stream can create regions of low Richardson number, triggering the generation of Kelvin-Helmholtz waves that evolve into turbulence [6]. The presence of an upper-level jet stream is often accompanied by a tropopause folding phenomenon, which further intensifies vertical wind shear and stability of stratification, thereby increasing the likelihood of CAT occurrence [7]. For example, Ştefan [8] and others, using model products and satellite observation data, found that severe turbulence events in Romanian airspace are often closely related to tropopause folding. Additionally, Imazio [7] and colleagues, combining high-resolution aircraft detection data, found that CAT events over Antarctica are significantly associated with strong wind shear and horizontal deformation fields. However, research on the relationship between tropopause folding and CAT remains relatively limited.

The Tibetan Plateau is the highest elevated heat source in the world, with an average altitude of over 4,000 meters and an area of 2.5 million square kilometers. Under the combined influence of factors such as the subtropical westerly jet stream, dynamic suction, and intense deep convection, the region becomes an active zone for the exchange between the troposphere and stratosphere [9]. Satellite data show that the tropopause height over the Tibetan Plateau is higher than that of surrounding areas in summer, while the opposite occurs in winter [10]. Reanalysis data indicate that this area is a hotspot for tropopause folding, and traditional sounding data may underestimate the frequency of tropopause folding events [11]. Previous studies have shown that the frequent tropopause folding in this region significantly affects local weather and climate processes.

Due to its unique geographical conditions, air transport is the primary means of access to and from the Tibetan Plateau. However, the complex weather conditions significantly increase the likelihood of CAT occurrence in the region, severely impacting flight operations [12]. Although previous studies have identified potential sources of CAT in the area, such as mountain waves and thunderstorms, the role of tropopause folding as an important trigger and its impact on flight activities during the cruising phase still require further investigation. Therefore, this study focuses on the relationship between tropopause folding and CAT in the Tibetan Plateau region, aiming to provide scientific evidence to enhance aviation safety in the area.

2 Data and Methods

2.1 Data Description

CAT is a small-scale weather phenomenon, and aircraft are the primary platform for measuring CAT. Air traffic control departments typically obtain information on the intensity, location, and altitude of CAT through pilot reports (PIREPs), but these reports are subjective and often lack precision. This study utilizes QAR data from an Airbus A320 for the period from January to December 2014. By extracting turbulence information from 1Hz-sampled overload data, the study records the location and altitude of CAT occurrences. To ensure data quality, anomalous data points were removed, and only records from the cruising phase were analyzed. According to the Airbus manual, overload values greater than 0.2 are defined as light turbulence, 0.2 to 0.5 as moderate turbulence, and greater than 0.5 as severe turbulence.

This study analyzed data from 1,924 flight segments. The flight path heatmap (Figure 1a) shows that the route from Chengdu to the Plateau is relatively fixed, flying near 30°N in an east-west direction, with flight altitudes concentrated between 30,000 and 37,000 feet (Figure 1b), corresponding to a pressure of about 200-250 hPa. Using the pressure-altitude conversion formula, the turbulence altitudes were transformed into pressure levels. The volume of flights to the Tibetan Plateau shows significant seasonal variation, with the highest number in summer (607 flights) and the lowest in winter (339 flights). To avoid the impact of differences in the number of flight segments on the statistical results, this study uses the turbulence frequency (turbulence occurrences/flight segments) for comparative analysis (Figure 1c).

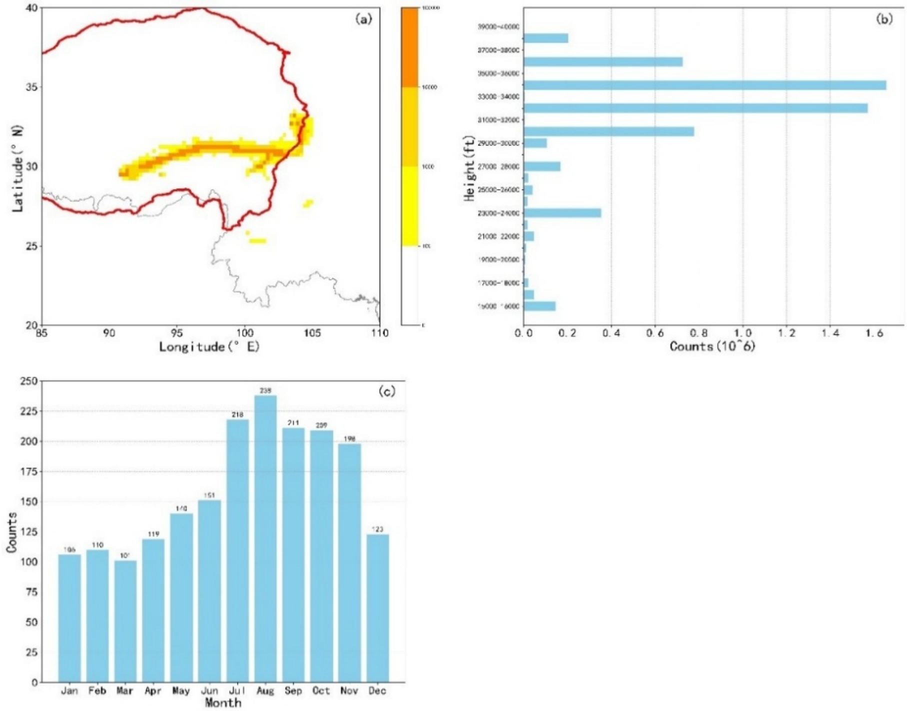

Fig. 1. (a) Flight trajectory heatmap of all flights in 2014, with the red solid line representing the contour of the Qinghai-Tibet Plateau. (b) Flight altitude distribution chart, with the numerical unit in 10^6 feet. (c) Monthly flight frequency statistics, showing the number of flights per month.

This study uses the ERA-5 dataset from the European Centre for Medium-Range Weather Forecasts (ECMWF), with a spatial resolution of 0.25°×0.25°, a temporal resolution of 1 hour, and 137 vertical layers. The dataset includes physical variables such as geopotential height, temperature, specific humidity, horizontal wind, and vertical wind. Data from 2014 were selected, with the analysis covering the region from 85°-

110°E and 15°-45°N, which encompasses the Tibetan Plateau and the flight area. Additionally, monthly average data for potential vorticity and U-wind were used. In the seasonal division, winter is defined as the months of January, February, and December 2014, with the remaining months categorized accordingly.

2.2 Identification and Classification of Tropopause Folds (TF)

This study uses the three-dimensional labeling algorithm developed by Škerlak et al. to identify tropopause folding (TF). The algorithm inputs include three-dimensional potential vorticity, potential temperature, specific humidity, and surface pressure. It determines the pressure levels of the 2 PVU isentropic surface and the 380K potential temperature isentropic surface, and then calculates the upper (Pu), middle (Pm), and lower (Pl) pressure levels of TF, as well as the thickness ($\Delta P = Pm - Pu$) of the folding region on a grid-by-grid basis.

Traditional studies define tropopause folding with a thickness of 50 hPa $\leq \Delta P \leq$ 200 hPa as shallow folding, 200 hPa $\leq \Delta P \leq$ 350 hPa as moderate folding, and $\Delta P \geq$ 350 hPa as deep folding. However, due to the high elevation of the Tibetan Plateau, even shallow folds have their bottom closer to the surface, which affects the region differently compared to plains. Statistical analysis of the folding frequency in the study area for 2014 (Figure 2) shows that 50% of folds have a thickness of less than 67 hPa, 75% have a thickness of less than 87 hPa, and the frequency of folds with a thickness greater than 130 hPa is only 5%. Given that moderate folding is rare in this region, this study sets the threshold of 130 hPa, corresponding to the cumulative frequency of 95%, to define $\Delta P <$ 130 hPa as shallow folding and $\Delta P \geq$ 130 hPa as deep folding. Based on this, the temporal and spatial distribution characteristics of tropopause folding (TF) in the Tibetan Plateau for 2014 are analyzed.

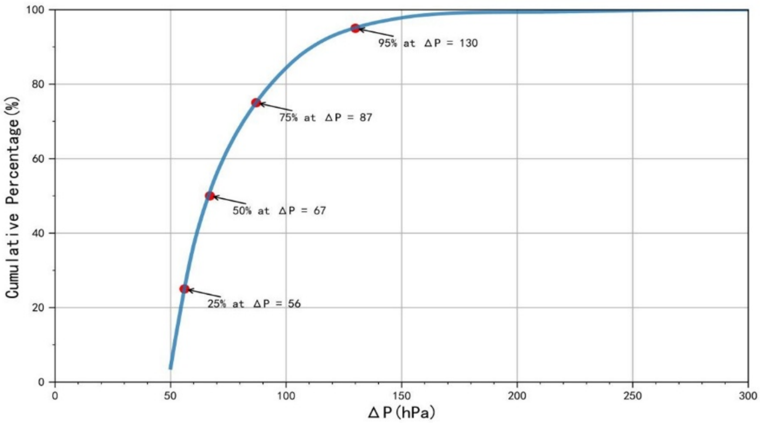

Fig. 2. displays the cumulative frequency of tropopause folding thickness (ΔP) occurring in the Tibetan Plateau region. The graph provides the corresponding ΔP values at cumulative frequencies of 25%, 50%, 75%, and 95%

3 Spatiotemporal Characteristics of Tropopause Fold (TF) in the Tibetan Plateau in 2014

The frequencies of shallow and deep tropopause folding in the Tibetan Plateau region exhibit a zonal distribution, complementing each other in the meridional direction, with significant seasonal variations (Figure 3). Winter is the season with the highest frequency of both shallow and deep folding. The high-frequency area of shallow folding is distributed around 29°N, with the highest center extending eastward from the eastern part of the Plateau, reaching a frequency of over 16%. Deep folding occurs farther north, around 31°N, with the highest frequency center located to the east of the Plateau, reaching about 4%. Comparing with the winter average westerly jet stream, the high-frequency area of shallow folding is located to the right of the jet's entrance, while the deep folding frequency is closer to the core of the jet stream.

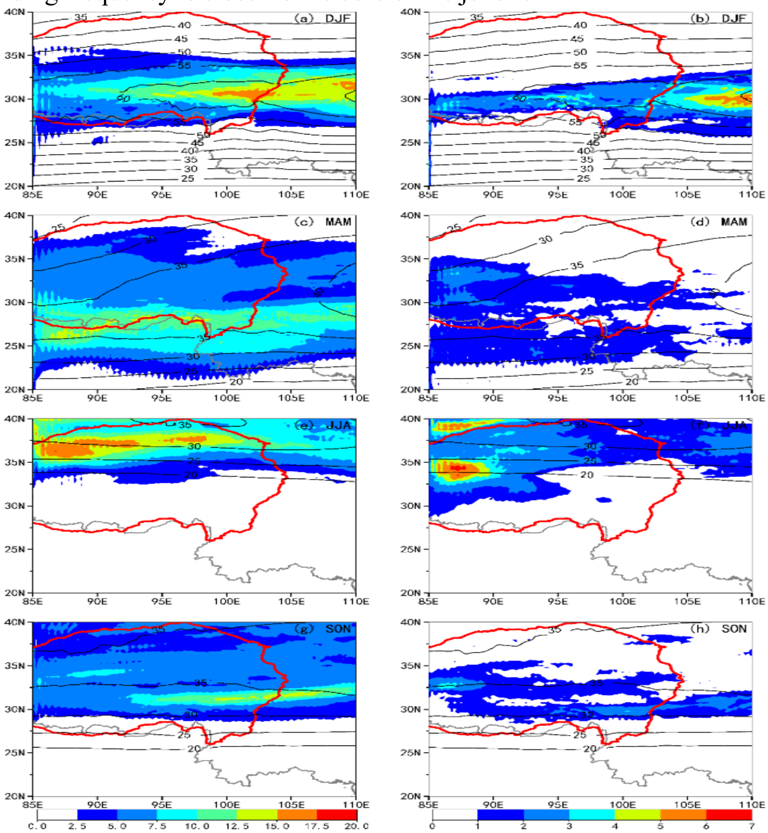

Fig. 3. Spatial distribution of the frequency of general folding (a, b, c, d) and strong folding (e, f, g) and strong folding (e, f, g, h) in winter (a, e), spring (b, f), summer (c, g), and autumn (d, h) (coloring). The black contour is the average U wind speed of 200 hPa in 2014, and the red contour line plots the outline of the Tibetan Plateau

In spring, the position of the jet stream changes little, but its speed and the shear intensity on both sides decrease significantly, leading to a reduction in the frequencies of both shallow and deep folding. The center of shallow folding is located north of 30°N, in the jet stream entrance region and to its left, with a frequency of about 13%. The center of deep folding is located in the southwestern part of the Tibetan Plateau, consistent with the position of the jet stream center. As the mid-latitude westerly jet moves northward, the high-frequency area of TF becomes decoupled from the jet, with the high-value zone shifting over the Himalayas to the South Asian subcontinent, where the frequency is similar to that in winter, suggesting that South Asian monsoon activity may be related to TF. In autumn, the westerly jet strengthens and shifts southward, once again influencing the Plateau. The high-frequency area of shallow folding is similar to winter, located to the south of the jet entrance, while deep folding is closer to the core of the jet. Meanwhile, the high-frequency area of folding remains over the South Asian subcontinent.

Figure 4 clearly illustrates the north-south migration characteristics of tropopause folding (TF) on a monthly basis. In January and February, the high-frequency area of shallow folding is located around 29°N, to the south of the westerly jet axis. As the jet weakens and shifts northward, the high-frequency area of shallow folding also migrates northward. Starting from May, the high-frequency area of shallow folding moves out of the Plateau, and in June, a high-frequency center appears in the southern part of the Plateau. The center reaches its southernmost point around 20°N in July and August. From September onward, the high-frequency area gradually shifts northward, but its intensity is weaker than in spring.In contrast, during the months of January to April and October to December, when the jet is stronger, the high-frequency area of deep folding is closer to the jet's axis center. In other months, it is located further south, compared to shallow folding. Overall, the deep folding area is generally located farther south, and tropopause folding is closely related to wind speed shear and wind speed magnitude.

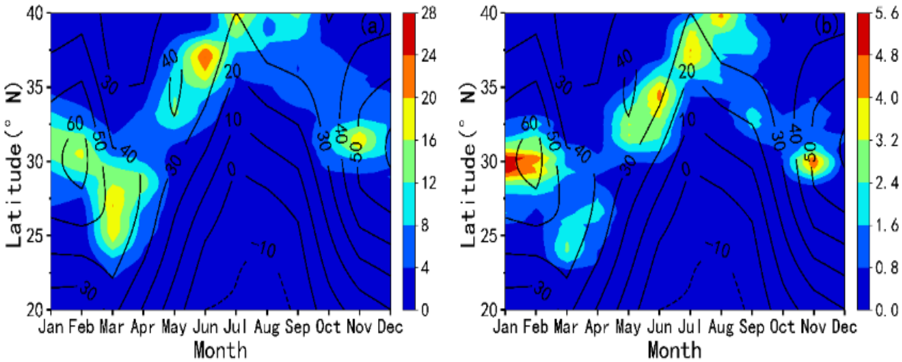

Fig. 4. shows the meridional variation of the frequency of general folds (a) and strong folds (b) along the 85°-110°E zonal average from January to December 2014 (shaded). The contour lines represent the monthly average zonal wind at 200 hPa.

4 Tropopause Fold and its Connection with Clear Air Turbulence (CAT)

In the winter of 2014, the number of flights was lower than in summer. After spatial and temporal matching, if a flight track point encounters a tropopause folding (TF) event, it is recorded as a TF encounter. Table 1 shows that winter had the highest frequency of TF encounters, especially in January and February, with more than 40 occurrences in each month, and nearly 50% of flights encountering TF events. From July to September, no TF events were encountered. After a TF event occurs, if an overload value greater than 0.25 is observed near the folding area (±1°), it is defined as a TF-induced turbulence (CAT) event. Table 1 shows that the highest frequency of TF-induced CAT occurred in February, with about 28% of TF events accompanied by CAT. The frequency of TF-induced CAT events in November and December also exceeded 20%.

Table 1. Total Number of Flight Sessions, Tropopause Fold Events, and Tropopause Fold-Induced Turbulence (CAT) Events for Each Month

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Total Flight	106	110	101	119	140	151	218	238	211	209	198	123
TF Event	49	46	23	20	15	1	0	0	0	23	38	25
TF-CAT	5	13	0	6	2	0	0	0	0	1	9	7

Since TF occurs in three-dimensional space, Figure 5 illustrates the spatial distribution of aircraft turbulence both within (Figure 5a) and below (Figure 5b) the tropopause folding (TF) region. It is evident that the CAT frequency below the TF region is significantly higher than within the TF itself. The areas of strong overload are concentrated during the high-altitude cruising phase, particularly to the west of the Hengduan Mountains (around 98°E), where strong turbulence occurs as the aircraft passes through the TF region. In contrast, the CAT frequency below the TF is higher, with strong CAT mainly occurring near the upper troposphere lower stratosphere (ZULS) region, especially during the descent phase. Even when far from the TF region, thermodynamic and dynamic effects still lead to intense CAT. Regardless of whether within or below the TF region, CAT primarily occurs in the plateau areas west of the Hengduan Mountains, suggesting that TF and the large-scale topography of the plateau are significant factors contributing to the occurrence of CAT.

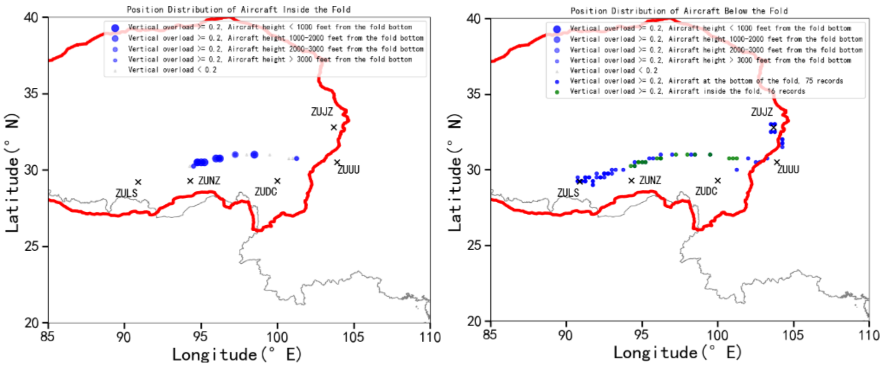

Fig. 5. shows the overload distribution characteristics within (a) and below (b) the Tropopause Fold (TF). In the figure, the red solid line represents the contour of the plateau.

5 Conclusion

This study analyzes the distribution characteristics of Tropopause Folding (TF) and its associated Clear Air Turbulence (CAT) in the Tibetan Plateau region in 2014. The results show that:

Due to the high elevation of the Tibetan Plateau, the lower boundary of TF is closer to the surface. Statistical analysis suggests that TF can be classified into shallow and deep folding categories based on the thickness of TF, with 130 hPa being the threshold for this classification.

The occurrence frequency of TF is highest in winter, reaching over 16%, primarily located around 31°N, which overlaps with the altitude of flight paths over the plateau. The frequency is lowest in summer, with the high-frequency zone shifting away from the plateau.

In winter, nearly 50% of flights encounter TF events. February sees the highest occurrence of TF-induced CAT, with about 28% of flights experiencing CAT when flying over TF areas.

Acknowledgments

The Open Foundation of Key Laboratory of Poyang Lake Wetlandand Watershed Research, Ministry of Education (Grant No. PK2023011)

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