

# The Hazard of Low-Altitude Flying in Mountainous Terrain: Analysis of a Fatal Incident in the High Tatras

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## Abstract

This study aims to examine flight safety risks associated with low-altitude operations in mountainous terrain. The research applies a case study methodology based on a fatal paragliding accident in the High Tatras (10 September 2023), integrating accident investigation data, meteorological analysis, and a comparative assessment of Slovak and Polish legislation. The findings identify severe thermal turbulence as the primary causal factor and reveal regulatory discrepancies affecting risk exposure. The study highlights the need for improved preventive measures and proposes the introduction of a fixed minimum flight altitude as a practical solution. The originality of this work lies in combining environmental and regulatory analysis to enhance aviation safety.

**KEY WORDS:** *aviation safety; mountain flying; paragliding accident; forensic accident analysis; High Tatras; thermal turbulence; aviation legislation; risk prevention.*

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## 1. Introduction

Low-altitude flying in mountainous areas represents one of the most demanding and riskiest categories in aviation. Complex terrain, unstable and often unpredictable meteorological conditions, limited maneuvering options, and increased pilot workload are factors that contribute to a high number of aviation accidents in these regions. In addition to these environmental constraints, limitations in human performance, particularly reduced situational awareness, delayed decision-making and increased cognitive load, further exacerbate operational risk. The relevance of this issue has increased in recent years with the growing popularity of recreational air sports, including paragliding, which often involve pilots operating in close proximity to terrain under visual flight conditions and without advanced onboard safety systems.

The academic literature has consistently emphasized the hazards associated with mountain flying. Studies from the Himalayas [9], the Alps, and the Colorado Rockies [8] confirm that meteorological phenomena such as mountain waves, turbulence, and rapid weather changes are among the leading causes of accidents. These dynamic atmospheric processes can develop rapidly and may not always be accurately predicted or detected, especially at lower altitudes. Furthermore, Controlled Flight Into Terrain (CFIT) has been identified as the most frequent fatal scenario in such environments [7], often resulting from a combination of environmental factors and pilot misjudgment. According to the Aviation Weather Handbook [6], reduced visibility, strong downdrafts, and rotor turbulence significantly increase the likelihood of loss of control or terrain collision, particularly for light and unpowered aircraft.

Despite the breadth of research conducted in other mountain ranges worldwide, there remains a lack of detailed risk analysis concerning the unique environment of the High Tatras. This mountain range forms the natural boundary between Slovakia and Poland and is characterized by steep relief, localized weather patterns, and high tourist density. Moreover, it is subject to distinct national approaches to airspace regulation, which may influence pilot behavior and

operational decision-making. The absence of harmonized regulatory measures and comprehensive safety studies tailored to this region represents a critical gap in current aviation safety research.

Specifically, the study presents a detailed examination of the events of 10 September 2023, when several paragliding incidents occurred in the High Tatras, one of which resulted in a fatality [1]. By analyzing meteorological conditions, pilot activity, and technical factors associated with the incident, the study aims to identify key risk determinants and highlight deficiencies in preventive practices. Particular attention is given to the interaction between environmental hazards and human factors, including pilot response to rapidly changing flight conditions. Furthermore, through a comparative analysis of Slovak and Polish aviation legislation [2, 4], the paper develops evidence-based recommendations intended to harmonize safety standards and introduce preventive measures that will enhance overall flight safety in this cross-border region. These recommendations are aligned with contemporary safety management principles, emphasizing proactive risk mitigation and the establishment of clear operational limitations.

## 2. Factors Influencing Flight Safety in Mountain Environments

Flight safety in a mountain environment is conditioned by the interplay of several specific factors, which can be divided into geographical and meteorological. Mountainous terrain is characterized by sharp changes in altitude, narrow valleys, and steep slopes, which place extreme demands on the pilot and significantly limit the aircraft's maneuvering space [6]. In such environments, pilots are often required to operate in close proximity to terrain, leaving minimal margins for error and reducing the time available for corrective actions. Navigation is further complicated by the similarity of peaks and a limited view of the horizon, particularly under marginal visual conditions. The risk is additionally increased by the presence of natural and man-made obstacles, such as power lines or cableways, which may be difficult to detect, especially in reduced visibility or high workload situations. These factors contribute to an increased cognitive load on the pilot, which may adversely affect situational awareness and decision-making processes.

Meteorological phenomena exert an even greater influence on flight safety in mountainous regions, as they are inherently more dynamic and less predictable than in flat terrain [6]. The interaction between airflow and complex topography leads to the formation of localized weather systems that can change rapidly over short distances and time intervals. As a result, pilots may encounter significantly different conditions within a single flight segment. The most significant threats include:

- **Mountain Waves and Rotors:** Strong airflow over mountain ridges generates oscillatory wave patterns that may extend to considerable altitudes and distances. These waves can produce severe vertical air movements, including powerful updrafts and downdrafts that exceed the performance capabilities of many light aircraft. On the leeward slopes, horizontal vortices (rotors) frequently form beneath these waves, creating zones of intense and often unpredictable turbulence. Such phenomena pose a severe threat to lightweight and recreational aircraft, including paragliders, which are particularly sensitive to sudden aerodynamic disturbances. Although lenticular clouds (*Alto cumulus lenticularis*) often indicate the presence of mountain waves, these visual markers may be absent under dry atmospheric conditions, making hazard detection more challenging [6]. Consequently, pilots may inadvertently enter hazardous areas without warning.
- **Thermal Turbulence and Local Circulation:** Due to intense solar radiation during the day, mountain slopes heat unevenly, leading to the formation of strong updrafts (thermals) and localized turbulence [6]. While this phenomenon provides the primary source of lift for gliding and paragliding activities, it simultaneously introduces significant instability into the airflow. Thermals can vary in strength and spatial distribution, resulting in abrupt changes in lift and control responsiveness. The daily cycle of mountain and valley breezes further contributes to the complexity of the local circulation system. During daytime, valley breezes generate upslope winds that enhance convective activity, whereas nighttime mountain breezes cause cold, dense air to descend into valleys. These descending air masses can lead to sudden reductions in lift and increased sink rates, particularly during critical phases of flight such as approach and landing. The variability of these processes requires continuous pilot monitoring and rapid adaptation to changing conditions.
- **Reduced Visibility:** Fog formation represents one of the most serious operational risks in mountainous environments. Valley fog typically forms as a result of cold air accumulation in low-lying areas during the night, while upslope fog develops when moist air is forced to rise along terrain features. In both cases, there is a significant reduction or complete loss of visual orientation, which dramatically increases the risk of Controlled Flight into Terrain (CFIT) [6]. In addition, rapidly forming cloud layers can obscure terrain features and eliminate visual reference points essential for safe flight under visual flight rules (VFR). The absence of reliable visual cues may lead to spatial disorientation, particularly for pilots operating without advanced instrumentation, further increasing the likelihood of navigation errors and terrain collisions.

Understanding the interaction of these geographical and meteorological factors is essential for effective risk assessment and the development of appropriate mitigation strategies in mountain aviation operations. Their combined effect creates a highly complex operational environment in which even minor deviations from safe flight parameters can lead to critical situations.

### 3. Analysis of the 10 September 2023 Incident

The date of 10 September 2023 was an extremely challenging day for rescue services in the High Tatras, mainly due to several aviation events involving paragliders. The occurrence of multiple incidents within a relatively short time frame indicates the presence of highly unstable atmospheric conditions affecting a broader area rather than an isolated local anomaly. The most serious of these incidents, which ended fatally, provides a detailed insight into the accumulation and interaction of risks in the mountain environment [1]. It illustrates how a combination of environmental, technical, and operational factors can rapidly escalate into a critical situation.

- **Flight and Accident Progression:** At 11:21 local time, a 28-year-old Polish paraglider took off from the official launch site near Skalnaté Pleso. The pilot held a valid license since 2015 and had considerable flight experience, having logged over 117 flight hours in 2023. He was flying a modern EN C category paraglider, designed for experienced pilots and characterized by higher performance but also increased sensitivity to pilot input and atmospheric disturbances. The planned flight path involved a westward traverse and a return, as illustrated in Fig. 1 [1]. The initial phase of the flight proceeded without reported complications, suggesting that the pilot operated within expected parameters under seemingly favorable visual conditions.



Fig. 1. Flight path record from the pilot's GPS device.

After approximately one hour of flight, while the pilot was in the Gerlachovský kotol area at an altitude of about 350 meters above the ground, a sudden, massive collapse of the right side of the canopy occurred at 12:24. This event was abrupt and asymmetric, leading to a rapid loss of aerodynamic stability. The collapse caused an immediate twisting of the suspension lines, which blocked the control lines and significantly reduced the pilot's ability to regain control over the glider [1]. At such a low altitude, the available time and vertical space for recovery were critically limited, leaving minimal margin for corrective action.

- **Meteorological Conditions:** At the time of the incident, visual meteorological conditions prevailed, with visibility exceeding 10 km. However, these seemingly favorable conditions masked the presence of intense thermal activity induced by solar heating of south- and southwest-facing slopes. This resulted in highly dynamic and vertically developed airflows. The development of cumulus humilis and mediocris clouds along the ridgelines confirmed active and potentially strong thermals in the area, as illustrated in Fig. 2. These convective phenomena are considered the most probable cause of the canopy collapse, as they can generate sudden vertical accelerations and localized turbulence exceeding the structural and operational limits of the wing [1]. This highlights the discrepancy between visual flight conditions and the actual aerodynamic environment, which may be significantly more hazardous.



Fig. 2. Meteorological situation in the Gerlachovský kotol area (view from another pilot's camera)

- **Rescue Attempt and System Failure:** The pilot reacted correctly to the critical situation and deployed the reserve parachute, demonstrating an appropriate emergency response under high-stress conditions. Although the reserve parachute opened within two seconds, which is within expected deployment parameters, its canopy subsequently became entangled in the lines of the still-rotating main glider. This entanglement prevented full deployment and effective stabilization of the descent. The investigation also revealed that the last repack of the reserve parachute was 92 days overdue, which may have negatively influenced its deployment characteristics and overall reliability [1]. The system subsequently entered an uncontrollable autorotation (spiral descent), significantly increasing the descent rate and reducing the effectiveness of any further corrective actions. The rotation also contributed to disorientation and increased aerodynamic loading on the system.
- **Consequences:** Upon impact, the pilot lost his helmet and suffered devastating head and spine injuries, which, according to the forensic report, were the direct cause of death. The severity of the injuries indicates a high-energy impact consistent with a vertical speed of approximately 15 m/s [1]. A toxicology examination confirmed no presence of alcohol or other intoxicants, thereby excluding impairment as a contributing factor. The outcome underscores the limited survivability of such accidents, particularly in rugged terrain where impact forces are amplified.

This incident is a prime example of how even an experienced pilot with modern equipment can face a situation that becomes unmanageable when a combination of adverse meteorological conditions and a subsequent failure of the rescue system occurs. It further demonstrates that in mountain environments, safety margins are often extremely narrow, and the interaction of multiple risk factors can rapidly overwhelm both pilot capability and technical safeguards.

#### 4. Legislative Framework in the High Tatras Region

The analysis of the incident is inextricably linked to the legal environment in which the flight took place. The High Tatras represent a unique operational area, as they form a cross-border national park managed by the Slovak Republic (Tatra National Park - TANAP) and the Republic of Poland (Tatrzański Park Narodowy - TPN). This geographical and administrative division introduces complexity into airspace governance and safety oversight. Although both countries are subject to common European regulatory frameworks, including EASA regulations and the Standardized European Rules of the Air (SERA), their national approaches to regulating low-altitude flights differ fundamentally. These differences influence not only operational practices but also the overall level of risk exposure in the region, particularly in relation to recreational aviation activities.

- **Slovak Legislation:** In Slovakia, flights over protected areas are regulated by Act No. 543/2002 Coll. on Nature and Landscape Protection (*Zákon č. 543/2002 Z. z. o ochrane prírody a krajiny*) [3] in conjunction with the Aviation Act (*Zákon č. 143/1998 Z. z. o civilnom letectve*) [2]. Slovak legislation does not establish a fixed, universally prohibited minimum flight altitude over TANAP. Instead, it adopts a conditional approach in which flights below 300 meters (approximately 1000 feet) above ground level are subject to an approval process involving the Ministry of the Environment of the Slovak Republic and the park administration. While this framework provides a degree of operational flexibility, it also introduces a level of regulatory ambiguity. In practice, recreational flights, including paragliding, may be conducted at relatively low altitudes without special authorization, provided that the pilot remains above the 300-meter threshold. This creates a regulatory gap in

which flights are permitted in altitude bands that may still be significantly affected by hazardous orographic and thermal phenomena. Furthermore, the absence of a clearly defined upper safety buffer above terrain may lead to inconsistent risk perception among pilots and limited enforceability of safety measures.

- Polish Legislation: Poland has adopted a significantly stricter and more precautionary approach. Based on a set of legal regulations (Prawo lotnicze [4], Ustawa o ochronie przyrody [5]) and supporting administrative measures, there is a strict prohibition on flights below an altitude of 3500 meters above mean sea level over the Polish part of the Tatras (TPN). This clearly defined altitude limit applies to all air traffic, with the exception of specifically authorized operations such as rescue missions, environmental monitoring, or scientific research. The restriction is formally published in the Aeronautical Information Publication (AIP Poland), ensuring its visibility, legal enforceability, and accessibility to all airspace users. This approach reflects a preventive safety philosophy, where risk is mitigated through the establishment of clear operational boundaries that effectively eliminate exposure to hazardous low-altitude conditions. As a result, pilot decision-making is guided by unambiguous regulatory constraints, reducing the likelihood of unsafe operational choices.
- Summary of Differences: While the Slovak side allows relatively free movement of air traffic, including sports aircraft and paragliders, above the 300-meter AGL limit, the Polish side has effectively excluded this category of aviation activity from the airspace above its national park for all types of aircraft. This fundamental difference in regulatory philosophy has a direct impact on the level of risk to which both pilots and individuals on the ground are exposed. The Slovak model, characterized by flexibility and case-by-case assessment, may inadvertently permit operations in conditions where environmental hazards are not sufficiently mitigated. In contrast, the stricter Polish model operates on the principle of proactive risk elimination by restricting access to high-risk zones altogether. Consequently, it significantly reduces the probability of incidents such as the one that occurred on 10 September 2023. From a safety management perspective, this comparison highlights the importance of clearly defined and consistently applied operational limitations as a key element of effective risk control in complex environments.

## 5. Policy Implications and Safety Recommendations

The synthesis of the analysis of the tragic incident of 10 September 2023 [1], together with the comparative evaluation of the legislative approaches of Slovakia and Poland [2, 3, 4, 5], yields a clear and significant conclusion: the current regulatory framework governing low-altitude flights over the Slovak section of the High Tatras (TANAP) is not sufficiently robust to effectively mitigate the risks inherent in a mountainous environment. The existing flexible approach, based on conditional approval of flights below 300 meters above ground level, appears inadequate in a context where hazardous meteorological phenomena, such as strong thermal turbulence and orographic disturbances, may occur well above this threshold. This regulatory gap allows flight operations to take place within altitude ranges that remain highly exposed to environmental hazards.

From a safety management perspective, this finding highlights the limitations of reactive or loosely defined regulatory systems in high-risk operational environments. In contrast, effective risk mitigation requires the implementation of clearly defined and consistently applied operational constraints that reduce exposure to known hazards. Based on the available evidence, this study proposes the introduction of a statutory minimum altitude applicable to all flight operations over the Slovak section of the Tatra National Park, with exceptions limited to rescue, state, and specially authorized missions. A reference value of approximately 2500 meters above mean sea level is recommended.

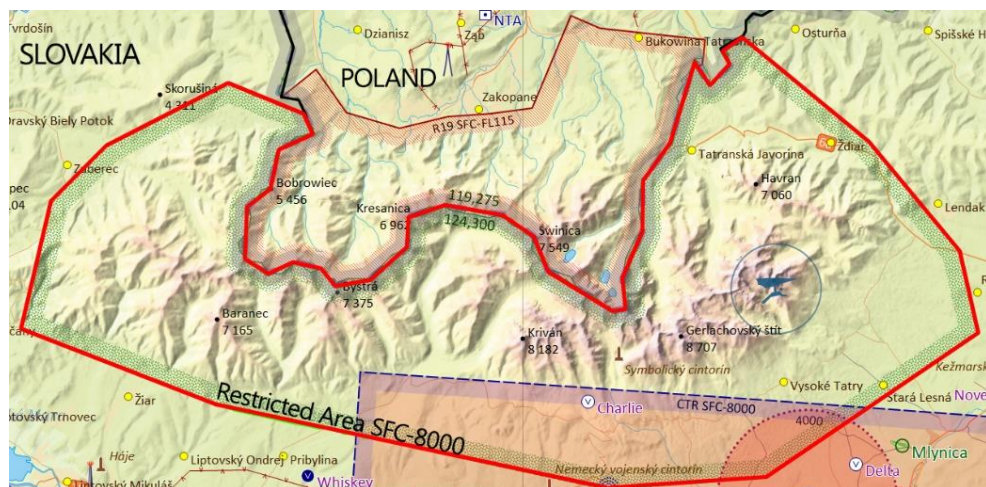


Fig. 3. Proposal for the establishment of a restricted flight altitude zone (Restricted Area SFC-8000 ft / ~2500 m) over the Slovak part of the High Tatras.

This altitude corresponds to the elevation of the main mountain ridges and would effectively relocate recreational air traffic above zones characterized by the most intense and unpredictable orographic and thermal activity. Such a measure would create a significantly larger safety buffer between aircraft and terrain, thereby increasing overall operational resilience, as illustrated in Fig. 3.

Benefits of this measure include:

- **Increased Safety:** A greater vertical margin above terrain would provide pilots with more time and maneuvering capacity to respond to in-flight emergencies, such as canopy collapse or loss of control. The accident of 10 September 2023, which occurred at approximately 350 meters AGL, would most likely have been avoided or its consequences significantly mitigated under such restrictions [1]. Additionally, increased altitude enhances the effectiveness of emergency systems, including reserve parachutes.
- **Regulatory Harmonization:** The introduction of a fixed altitude limit would contribute to the alignment of safety standards across the Slovak and Polish sections of the Tatras, reducing current regulatory discrepancies. Harmonized rules would facilitate better understanding among pilots operating in cross-border airspace and support a more consistent safety culture.
- **Clarity and Enforceability:** The publication of a clearly defined altitude threshold in aeronautical charts and the Aeronautical Information Publication (AIP) would ensure transparency for operators and significantly simplify enforcement for aviation authorities. Clearly defined rules reduce ambiguity in pilot decision-making and improve compliance rates.
- **Protection of Nature and Tourism:** Restricting low-altitude flights would contribute to reducing noise pollution and minimizing disturbance to wildlife, which is consistent with the primary conservation objectives of national parks. At the same time, it would decrease the risk to thousands of tourists present in the area, particularly in popular hiking zones located directly beneath frequently used flight paths.

The establishment of such a restricted airspace zone represents a standard and widely accepted tool within modern airspace management and aviation safety practice. Its implementation would constitute a proactive and systematic step toward enhancing flight safety, improving regulatory clarity, and ensuring sustainable coexistence between aviation activities, environmental protection, and tourism in this sensitive alpine region.

## 6. Conclusions

This study examined the hazards of low-altitude flight in mountainous terrain through an in-depth analysis of a fatal paragliding accident in the High Tatras on 10 September 2023. The findings indicate that the accident was caused by canopy collapse due to severe thermal turbulence, further exacerbated by the failure of the reserve parachute system following entanglement with the main wing. This sequence highlights the vulnerability of even experienced pilots when exposed to unstable meteorological conditions and limitations in emergency response.

The comparative legal analysis revealed a significant discrepancy between the Slovak and Polish regulatory frameworks. The Slovak system allows operations in altitude zones where meteorological hazards remain pronounced, whereas the Polish model, with its defined minimum altitude of 3,500 meters AMSL, effectively mitigates such risks through preventive regulation. This demonstrates the importance of clearly defined operational limits in reducing risk exposure.

The principal contribution of this study is the proposal to introduce a fixed minimum flight altitude of 2,500 meters AMSL over the Slovak section of the Tatra National Park. This measure would harmonize cross-border safety standards and reduce the likelihood of similar accidents, while supporting environmental protection and public safety.

Furthermore, the findings of this study highlight the need for continued research into the interaction between human factors, environmental conditions, and regulatory frameworks in mountain aviation. Future studies should focus on the development of integrated risk assessment models and the implementation of proactive safety management strategies that can further enhance operational safety in similarly complex and high-risk environments.

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