Wind Shear Assessment Report for Paro International Airport

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Ugyen Lhamo
Met/Hyd Officer
Aviation Meteorology Section

Introduction

This report provides a comprehensive analysis of wind shear events at Paro International Airport, leveraging data from multiple sources, including Automated Weather Observation System (AWOS), Radar Wind Profiler (RWP), aviation stakeholders survey and safety risk assessment by the safety liaison officers. As per ICAO Annex 3, Chapter 7, Wind shear warnings should be prepared by the meteorological office for aerodromes where wind shear is considered a safety factor. This assessment aligns with ICAO Annex 3 requirements for aerodromes where wind shear is considered a significant operational factor.

Definition of Wind Shear

Wind shear is a critical meteorological phenomenon, particularly significant in aviation safety, characterized by rapid changes in wind speed and/or direction over a relatively short distance. These variations can occur in both the horizontal and vertical planes, leading to turbulence and instability during flight operations, especially during takeoff, approach and landing phases. Britannica defines wind shear as a "rapid change in wind speed and/or direction over a relatively short distance." According to the Bureau of Meteorology (BOM), the changes can manifest either vertically or horizontally. ICAO Doc 9817 elaborates that wind shear ranges from small-scale eddies and turbulence to large-scale atmospheric flow patterns, affecting various layers of the atmosphere. Airbus refers to wind shear as the "invisible enemy to pilots," highlighting its potential to disrupt flight paths and compromise aircraft control, particularly in regions like Paro International Airport, where complex terrain can amplify these effects.

Causes of Wind Shear

Wind Shear can be attributed to several atmospheric and environmental mechanisms. These mechanisms are influenced by dynamic weather patterns, terrain interactions, and boundary layer processes. The primary causes of wind shear at airports like Paro International Airport include the following:

1. *Thunderstorms:* Convective systems, particularly thunderstorms, are known to generate intense vertical and horizontal wind shear. The rapid development of cumulonimbus clouds creates downdrafts and microbursts, resulting in sudden changes in wind speed and direction. Microbursts, often associated with severe thunderstorms, pose a critical hazard to aircraft, particularly during low-altitude flight phases such as approach and departure. The outflows from these downdrafts can create significant velocity gradients that are difficult to detect in real time.

2. *Low Level Jet Streams:* Low-level jet streams are narrow bands of high-velocity winds found in the lower troposphere, typically within 500 to 2000 meters above ground level. These jets, often observed during nighttime or early morning, can create significant horizontal and vertical wind shear, especially during periods of atmospheric stability. The interaction between the surface winds and the higher velocity jet stream can result in dangerous shear conditions for aircraft during takeoff and landing operations.
3. *Mountain Waves :* Orographic influences play a major role in generating wind shear, particularly in regions with complex terrain. When strong winds interact with mountainous topography, they create lee-side turbulence and standing wave patterns known as mountain waves. These waves induce vertical wind shear, often resulting in severe turbulence and abrupt wind shifts. Airports surrounded by mountains, such as Paro International Airport, are particularly susceptible to the effects of mountain waves, which can occur even in relatively stable atmospheric conditions.
4. *Temperature Inversions:* A temperature inversion occurs when a layer of warmer air overlies cooler air near the surface, creating a stable atmospheric layer. Inversions suppress vertical mixing, causing large wind speed differences between the inversion layer and the surface. This vertical wind shear is particularly dangerous when inversions occur at low altitudes, as aircraft may encounter significant changes in wind velocity during ascent or descent through the inversion layer. These conditions are common during calm, clear nights when radiational cooling enhances inversion strength.
5. *Obstacles and Terrain Induced Shear :*Localized wind shear can also result from airflow disruptions caused by obstacles such as buildings, forests, or mountainous terrain. The interaction between airflow and these obstacles creates localized vortices and eddies, leading to sudden wind shifts.

Significance of Wind Shear in Aviation

Wind Shear is one of the most critical meteorological phenomena affecting aviation safety, particularly during take off, landing and low level flight operations. It can result in significant deviations from an aircraft's intended flight path. Wind Shear can create conditions where an aircraft's performance is momentarily reduced, leading to stalled engines, hard landings or missed approaches. From an aerodynamic perspective, wind shear alters the relative airflow over an aircraft's wings, causing fluctuations in lift and thrust that can be difficult for pilots to counteract.

The unpredictability of these wind shifts, coupled with the limited reaction time available to pilots, makes wind shear a formidable hazard in aviation operations. In regions with complex terrain, such as Paro International Airport, the influence of wind shear is further amplified by the interaction between the atmospheric boundary layer and the surrounding topography, creating conditions of severe turbulence and abrupt wind shifts. To ensure flight safety and minimize the risk of aviation accidents, the International Civil Aviation Organization mandated the monitoring and reporting of wind shear at aerodromes where it is considered a safety factor.

Methodology : Data Sources

AWOS:

The AWOS stations at Paro International Airport are installed at two critical locations: near Runway 15 and Runway 33, 300 meters from each runway's end. This results in a separation distance of approximately 1300 meters between the two stations which complies with ICAO's Manual on Low-Level Wind Shear (Doc 9817) where it states that AWOS stations positioned within 4km of each other allow for the calculation of horizontal wind shear by comparing wind data from both locations. Each AWOS station provides high resolution meteorological data at 2-minute intervals, which includes wind speed and direction. These parameters are captured using ultrasonic anemometers, offering precise and reliable measurements of wind speed and directional shifts. The sensors are connected via fiber communication lines to the server located in the Meteorological Office Room at the airport. The data is streamed continuously to the server, where it is processed, displayed and archived.

RWP:

The Radar Wind Profiler (RWP) is located near Runway 15, as shown in the schematic. The profiler provides vertical profiles of wind speed and direction, allowing the detection of wind shear at various altitudes. The LAP3000 system with four panels is capable of measuring wind profiles up to 3000 meters above ground level. RWP operates by emitting an electromagnetic pulse from its antenna and a small portion of this pulse is reflected back to the profiler due to inhomogeneity in the refractive index of the atmosphere, primarily caused by small scale turbulence and temperature variations. The returned signal, or echo, is received and analyzed to determine wind speed and direction at various altitudes.

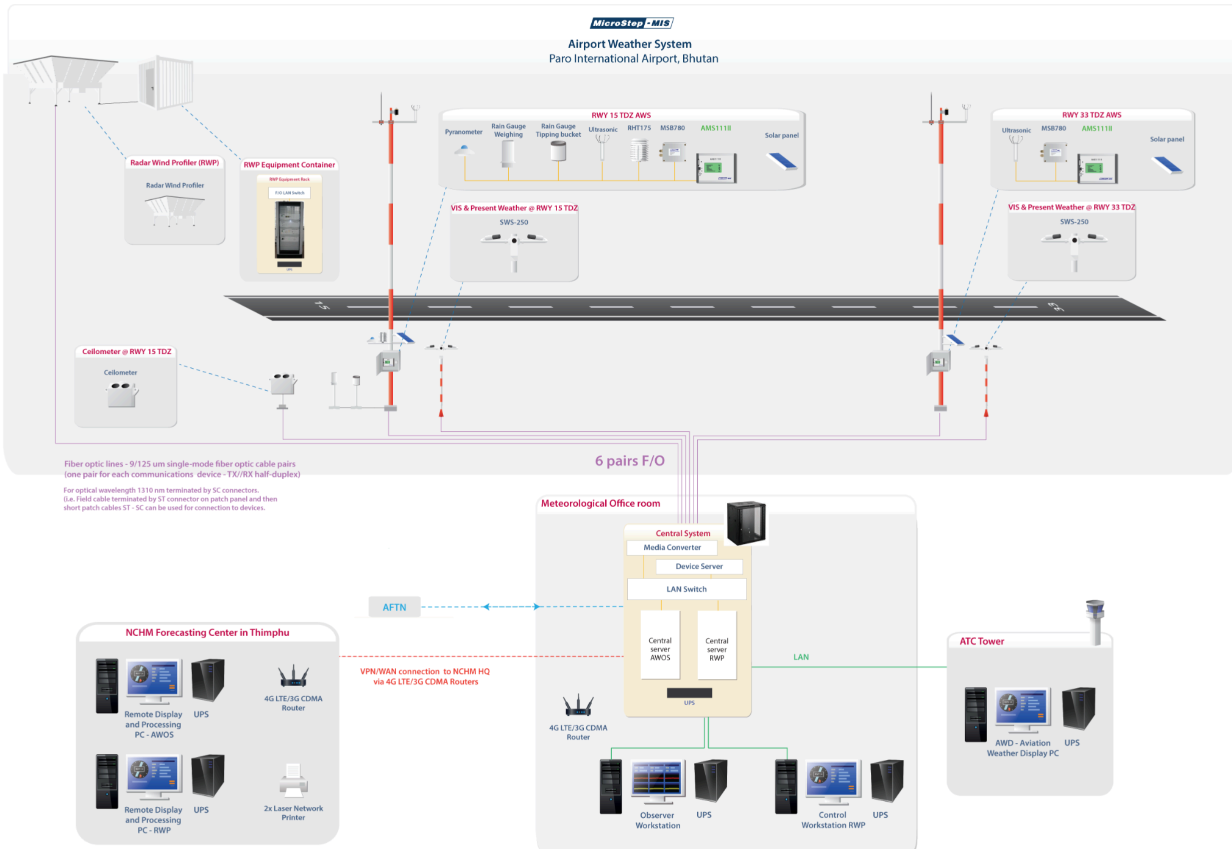


Figure 1: Visual Schematic of AWOS and RWP at Paro International Airport

Survey:

In addition to quantitative data from AWOS and RWP systems, qualitative data was also gathered through surveys targeting pilots, ATCs and MET personnels at Paro International Airport. These surveys aimed to capture subjective experiences with wind shear, adding valuable insights into the operational challenges posed by wind shear.

Data Processing and Findings

1. Position Vectors of Wind shear

AWOS data for every second was collected over the past five years. This data provides wind speed and direction readings at two locations RWY 15 and RWY 33. These stations provide wind speed and direction readings at their respective locations on the runway. However, due to the data being merged rather than segregated by location, traditional methods of calculating horizontal wind shear between two points could not be directly applied. Instead, the approach taken to analyze the shear was based on temporal analysis with the limitation of not being able to distinctly analyze each point's contribution.

The formula for the wind shear rate was expressed as :

Wind shear : $\frac{\Delta V}{\Delta t} = \frac{V\,(t+1) - V(t)}{\Delta t}$;

Where : ΔV is the change in wind speed (knots) over time interval
Δt is the time interval (seconds)

The data was preprocessed and visualized in python using the shear formula.

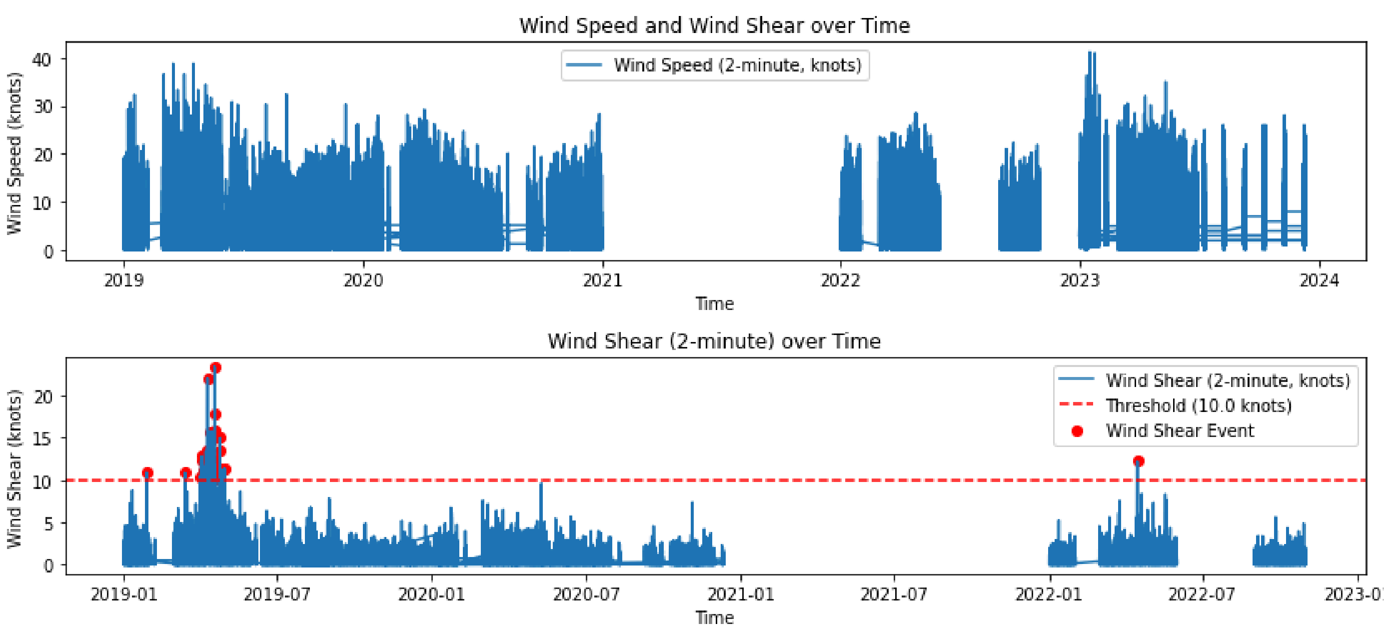


Figure 2 : Temporal Analysis of Wind Speed and Shear from 2019 to 2023

Figure 2. consists of two plots representing the wind speed and wind shear over a five year period using secondly AWOS data analyzed in 2-minute intervals. The plot shows fluctuation in wind speed with several significant peaks where wind speeds exceed 30 knots. In the bottom figure, wind shear is measured in knots, with values ranging from 0 to 25 knots. A threshold of 10 knots has been indicated on the graph, marking the wind shear events that exceed this critical value. The red circles indicate significant wind shear events that could pose risks to aircraft operations. The wind shear values generally remain below the 10 knot threshold, with occasional spikes indicating significant wind shear events. The largest cluster of wind shear events is concentrated around mid-2019, with shear values reaching up to 20 knots. The presence of significant wind shear events especially during periods of high wind speed, indicates potential hazards for aircraft on approach or departure. To maintain the integrity of the data and ensure compliance with QMS and ICAO requirements, the gaps in the dataset were not interpolated. To preserve the accuracy and reliability of meteorological records, it is strongly recommended to avoid data manipulation such as interpolation.

2. Actual Horizontal Shear Calculation by Segregation

For the period from August 2023 to July 2024, the wind speed and direction data from two locations were segregated and analyzed to calculate horizontal wind shear. The threshold for wind shear events was set at 15 knots, in accordance with the ICAO Doc 9817 low level wind shear manual, which defines critical wind shear thresholds relevant to aviation safety.

The wind data from the two positions were manually segregated using Excel to ensure the datasets were distinct for each location. This manual segregation was necessary to perform a precise horizontal shear analysis across two points. The data was then processed for component analysis and vector difference calculations, using mathematical equations described below and further visualized in Python for detailed insights.

To analyze the horizontal shear, wind speed and direction data at both runway points were converted into their respective zonal and meridional components.

$$u = -V.sin(\theta)$$
$$v = -V.cos(\theta)$$

Where:

- V is the wind speed in knots,
- θ is the wind direction in degrees,

- u represents the east-west (zonal) component of the wind
- v represents the north-south (meridional) component of the wind

Once the components of the wind were calculated, the vector difference between the two points was computed to derive the horizontal wind shear, given by:

$$\Delta u = u_{33} - u_{15}$$

$$\Delta v = v_{33} - v_{15}$$

The magnitude of the wind shear was calculated using the Euclidean distance formula to combine the zonal and meridional wind differences:

$$\text{Shear Magnitude} : \sqrt{(\Delta u)^2 + (\Delta v)^2}$$

$$\text{Shear Direction} : tan^{-1}\left(\frac{\Delta u}{\Delta v}\right)$$

$$(\text{Degrees}) = \left(\frac{Shear\ Direction.180}{\pi} + 360\right) mod\ 360$$

After performing the manual segregation in excel and component analysis in python, the processed data was further analyzed for visualization in python.

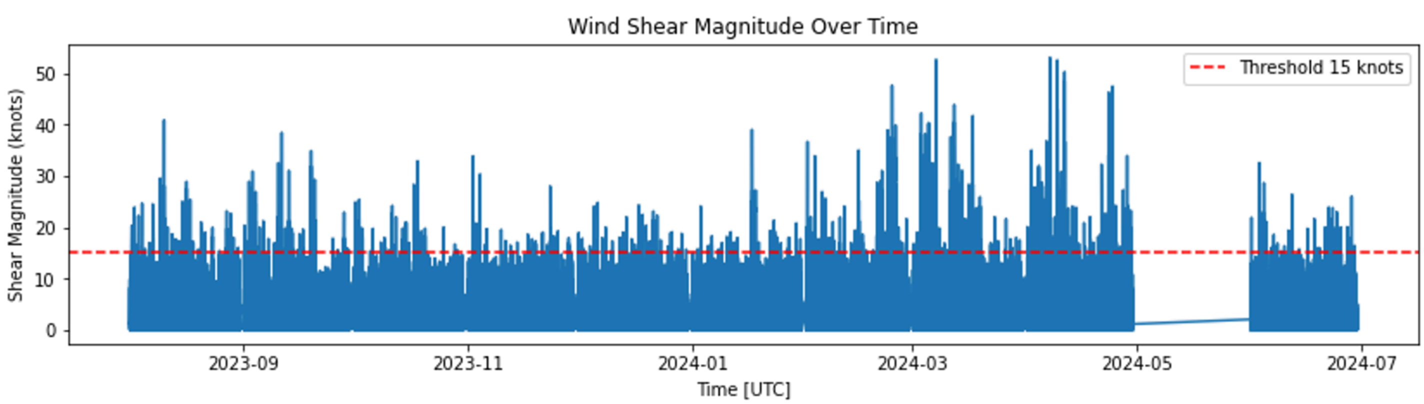


Figure 3 : Horizontal wind shear analysis over time (2023-2024)

The plot represents the wind shear magnitude over time for the period from August 2023 to July 2024, based on wind speed and direction data from RWY 15 and RWY 33 where the wind shear is plotted against time, with a 15-knot threshold indicated by a red dashed line. Wind shear events that exceed this threshold are crucial for identifying periods of high risk, where the aircraft may experience sudden and severe changes in wind speed and direction. The majority of the wind shera values hover the 15-knot threshold, indicating relatively mild wind shear events that are unlikely to pose significant risks. However, frequent spikes above the threshold are clearly visible throughout the data, particularly around November 2023, March 2024 and April 2024. These spikes represent periods of intense wind shear with magnitudes reaching up to 40-50 knots in some cases.

Notably, the period between February 2024 and April 2024 shows a high frequency of wind shear events above 15 knots, suggesting a sustained period of atmospheric instability. This could be related to pre-monsoon disturbances in Bhutan. The seasonal variation in the wind shear events and significant spikes in shear magnitude during winter months (December to March) could suggest increased wind shear activity during cold weather often associated with stronger pressure gradients and more variable wind conditions. The consistent exceedance of the 15-knot threshold at multiple points throughout the year signals a need for heightened operational awareness at Paro International Airport.

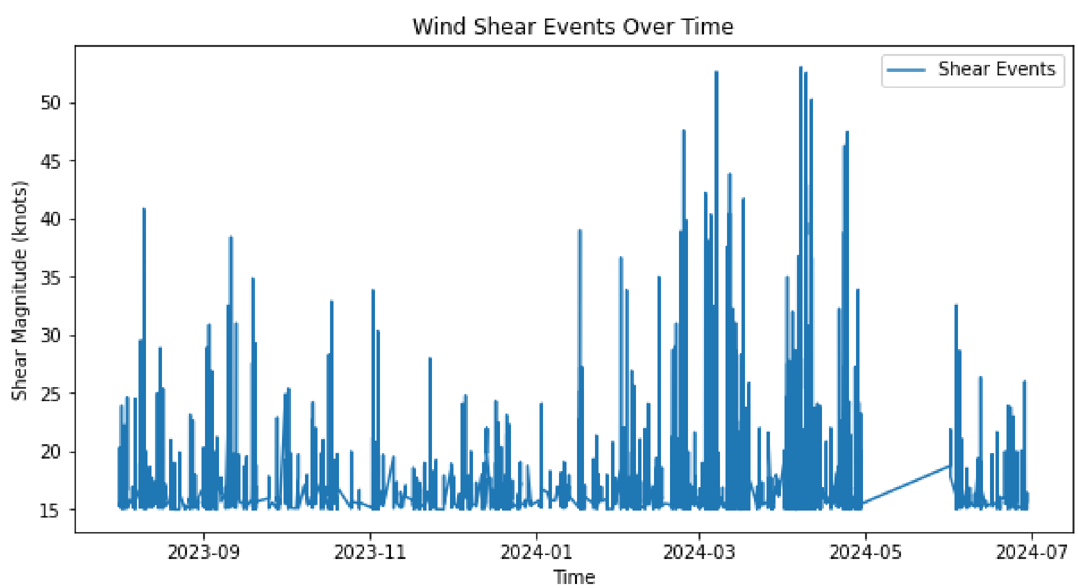


Figure 4 : Wind Shear Events over time (2023-24)

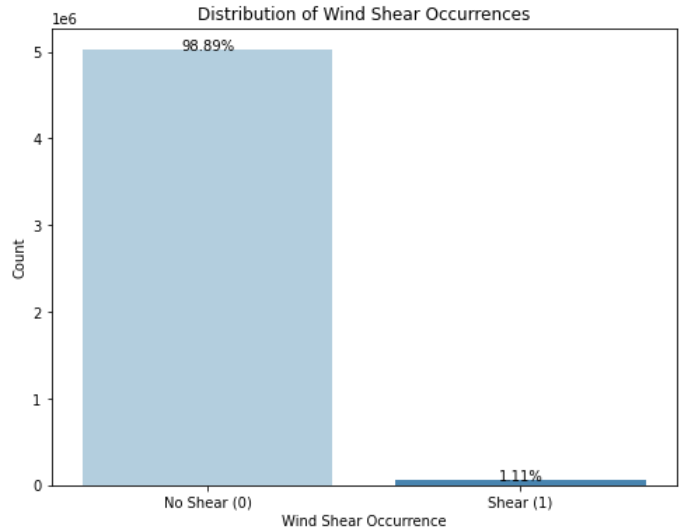


Figure 5: Probability of Wind Shear Occurrence

Figure 5 shows only 1.11% probability of wind shear occurrence over time. Since the data set is at secondly intervals, even though there are frequent spikes in shear magnitude, the time between these spikes may be long enough that "no shear" conditions dominate the dataset. This would result in a high count of "no shear" occurrences simply because shear events are transient and short lived compared to the periods of calm.

3. Vertical Wind Shear Analysis

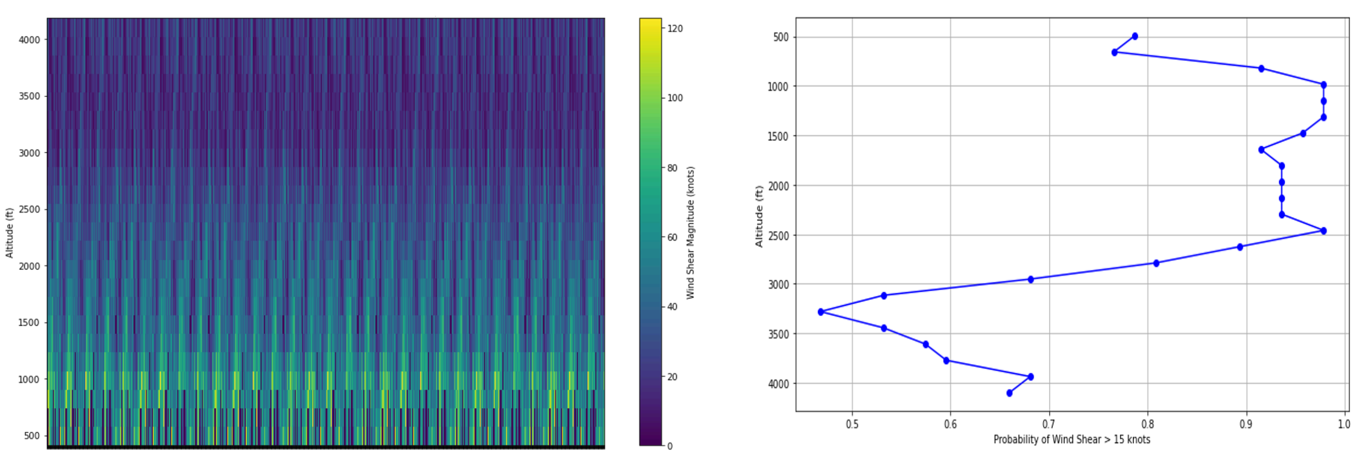


Figure 6 : Left: Heatmap of vertical Wind Shear and right : probability of wind shear

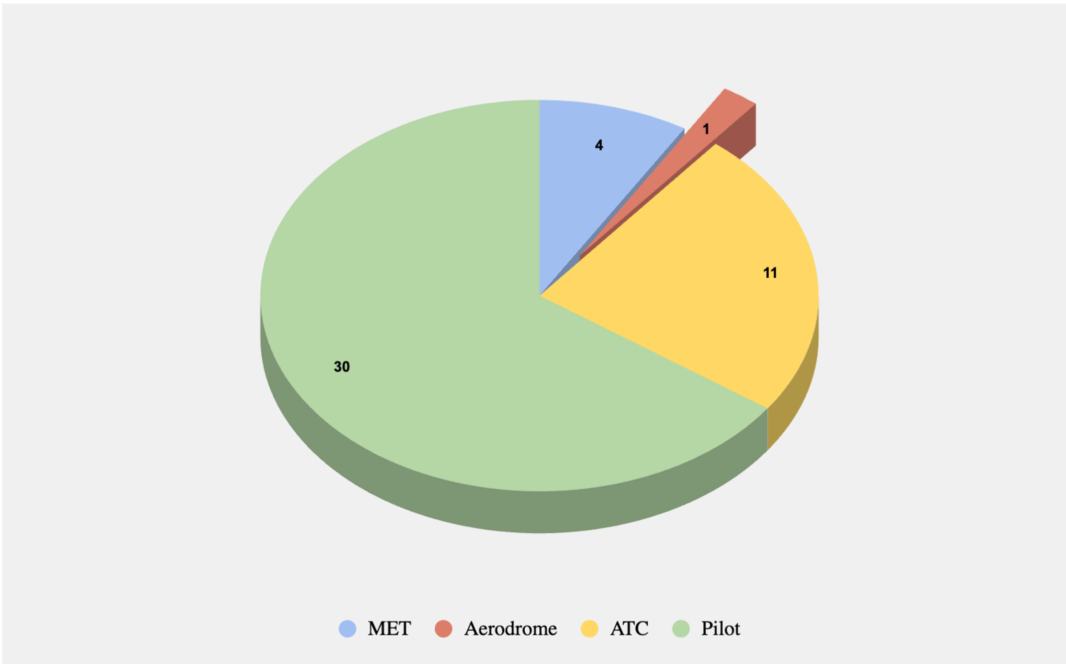
Figure 6 visualizes the vertical wind shear at RWY 15, measured by the Radar Wind Profiler (RWP) over a period from April to July. The data was processed from .mnd format, which limits long term analysis, so a few months were used to examine the wind shear characteristics over different altitudes. The heat map indicates that wind shear varies significantly with altitude. The strongest shear occurs in the lower levels from 500 ft and 1500ft. At these lower levels, the wind shear magnitude exceeds 60 knots with some isolated regions showing shear magnitudes close to 120 knots. At altitudes above 2000ft, the wind shear generally decreases in intensity, with fewer instances of significant shear. This indicates that while the lower atmosphere is prone to high shear, the air becomes more stable at higher altitudes.

The right plot shows the probability of encountering wind shear greater than 15 knots. The plot confirms the observation from the heat map that lower altitudes are particularly prone to hazardous wind shear conditions. There is a notable dip in probability around 1500-2000 ft, suggesting a transition layer where the effects of terrain or surface features are diminishing, leading to more stable conditions higher up.

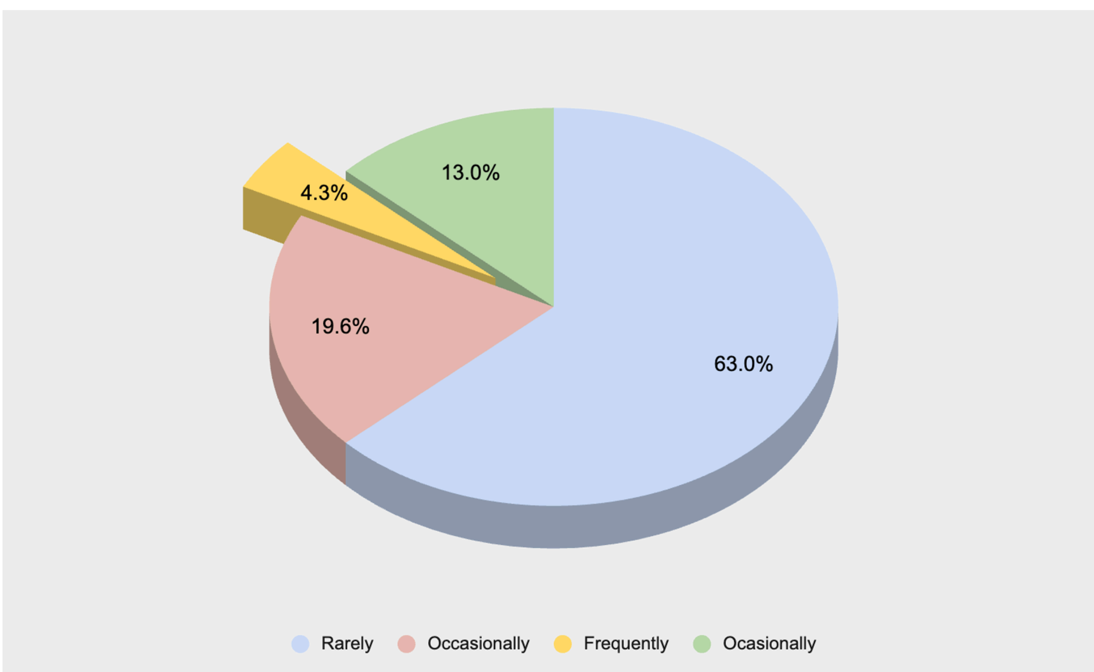
Survey outcomes

In addition to the meteorological data analysis, a survey questionnaire was distributed at Paro International Airport (PIA) to further enhance the comprehensiveness of the report. The results are as follows:

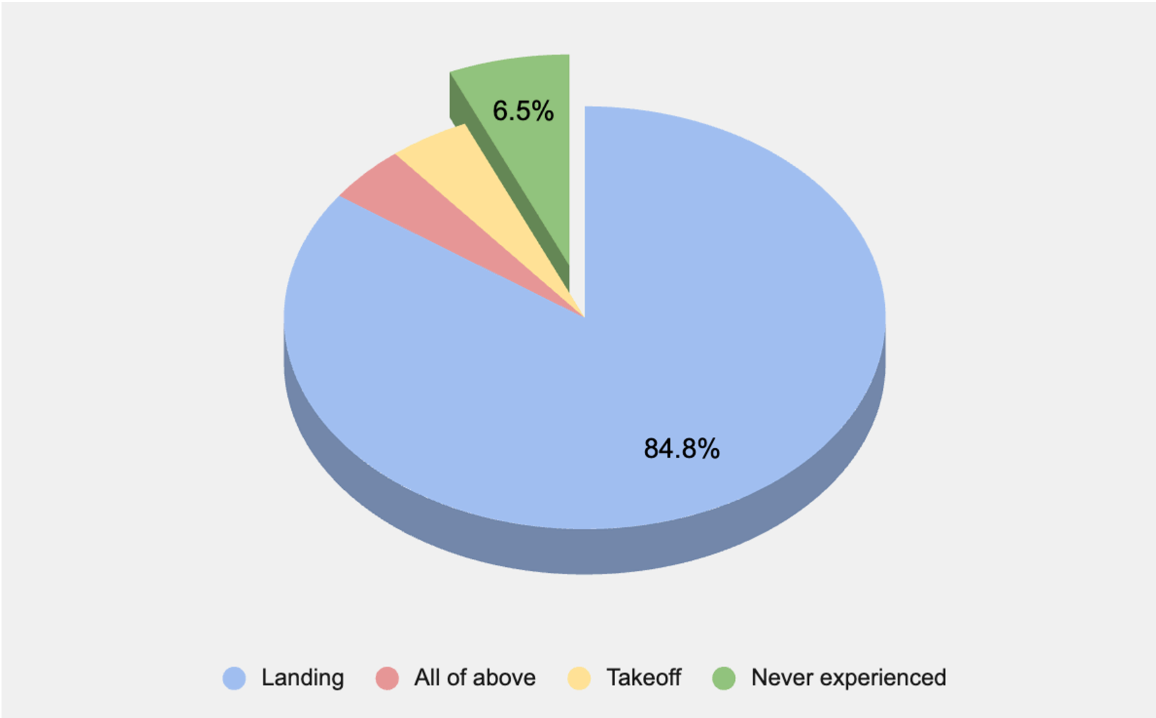
Question 1. What is your position at Paro International Airport?



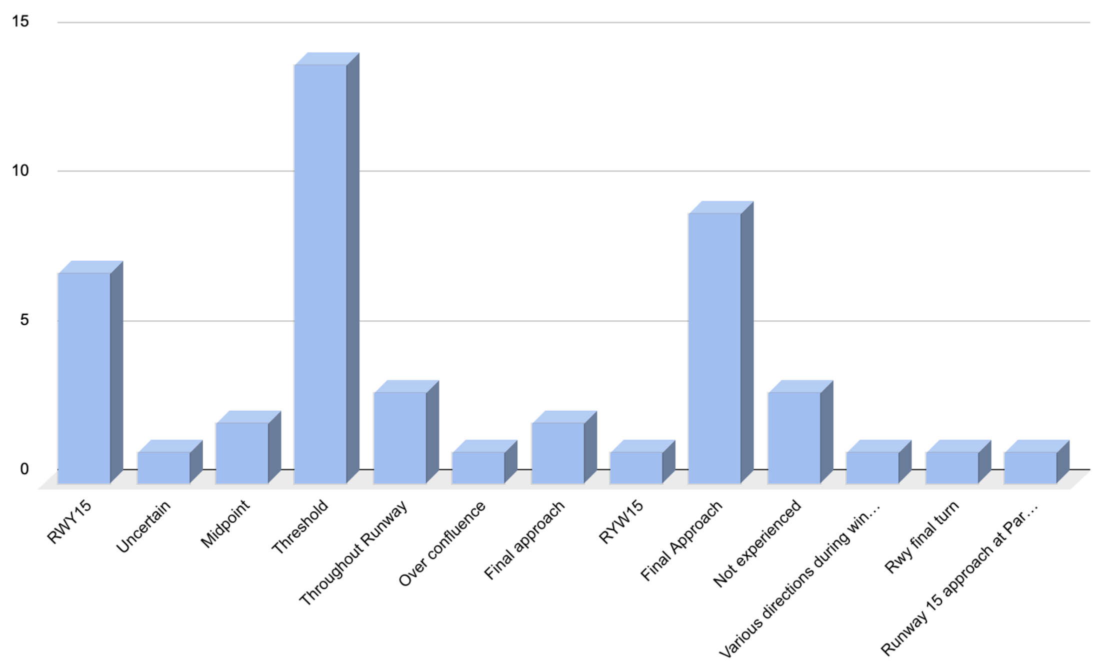
Question 2. What is your frequency of wind shear encounters?



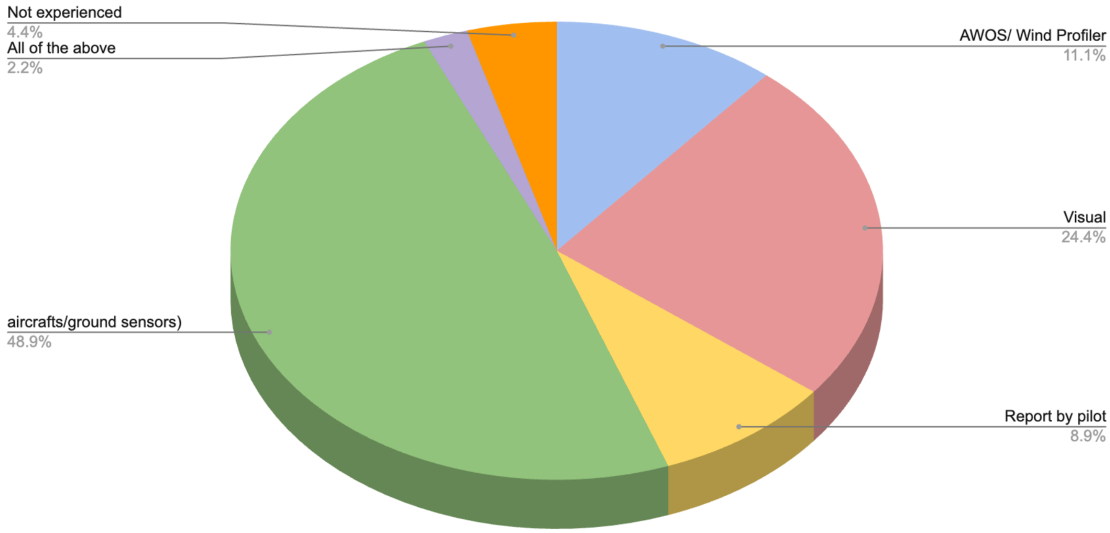
Question 3. What are the typical phases of flight during wind shear encounters?



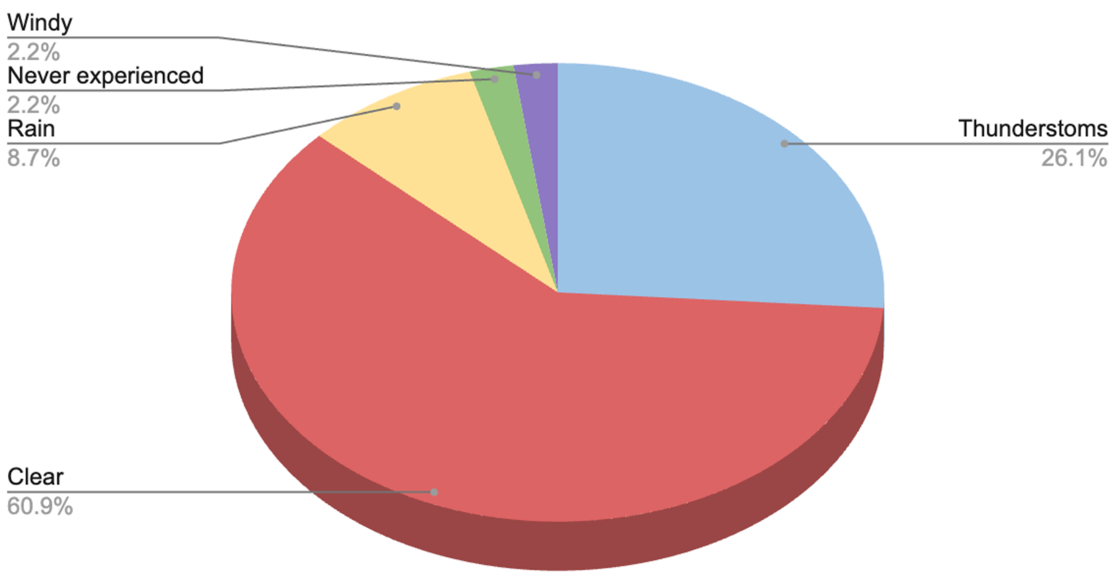
Question 4. Where did you encounter wind shear relative to the runway?



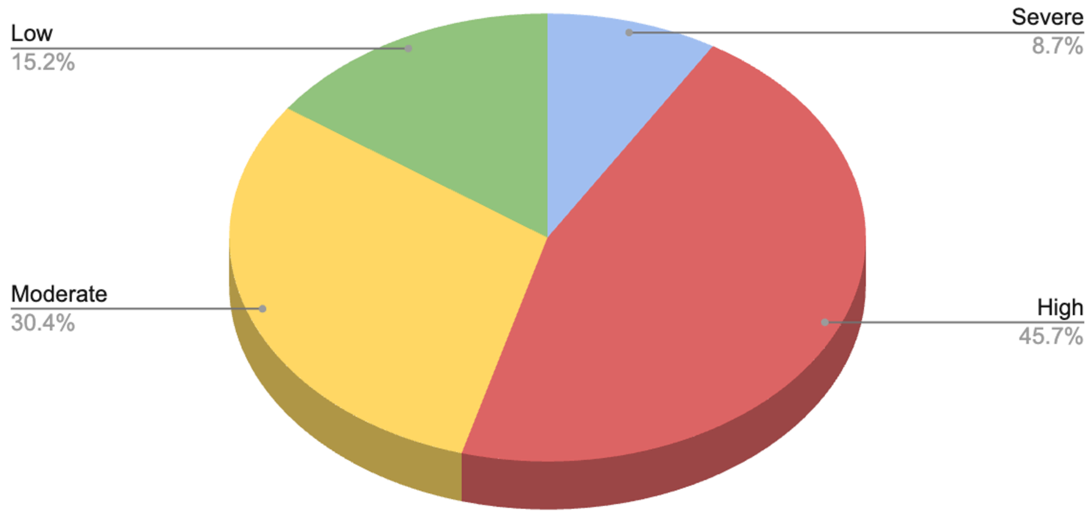
Question 5. How did you detect the wind shear?



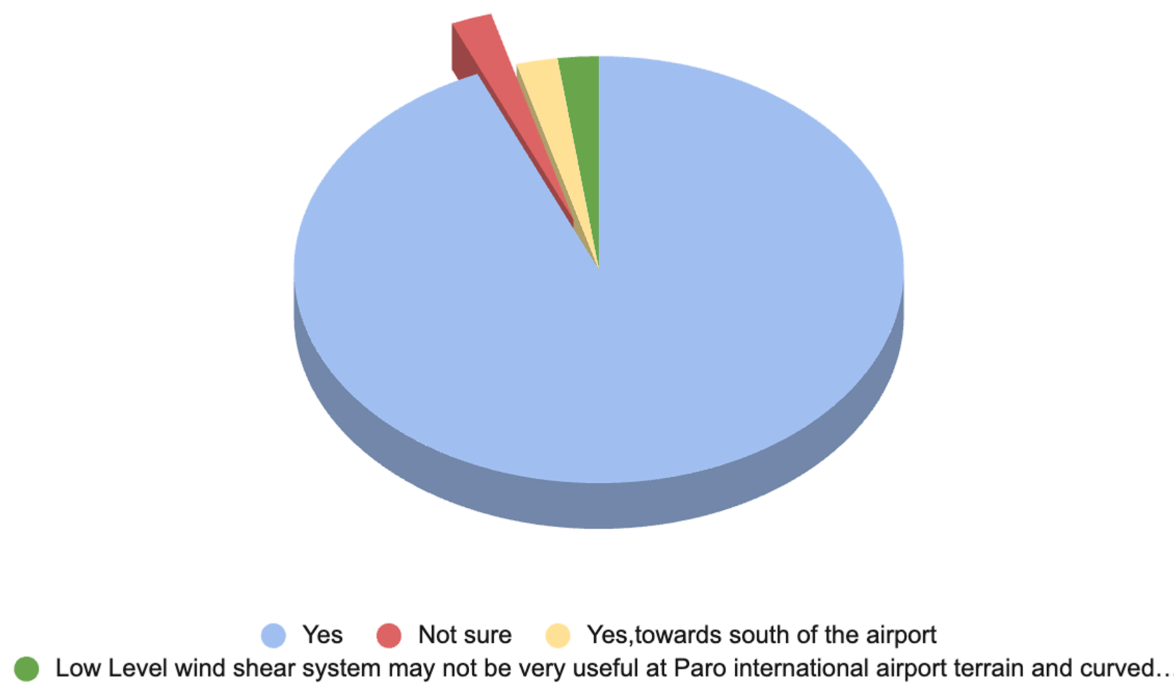
Question 6. What were the weather conditions during wind shear encounters?



Question 7. What is your perceived impact on safety with regards to Wind Shear?



Question 8. Would you recommend implementing a low level wind shear alerting system?



Risk Assessment Outcomes

Safety risk assessments play a critical role in ensuring the safe operation of aircraft. For this report, SMS liaison officers from Bhutan Civil Aviation (BCAA), the department of Air Transport (DoAT) and the National Centre for Hydrology and Meteorology (NCHM) conducted comprehensive safety risk assessments specifically targeting the implications of wind shear on flight operations at Paro International Airport.

1. Identification of Hazards: Wind shear was identified as a significant hazard affecting aircraft performance during critical phases of flights.
2. Evaluation of Risk Severity: The severity and likelihood of encountering wind shear events at Paro were analyzed from the met data and survey reports.
3. Identification of existing defense to control risks were discussed
4. The safety officers also discussed further actions to reduce risks associated with the hazard
5. Finally the residual risk scores were calculated after the mitigation measures were discussed.

The risk assessment for Wind Shear Evaluation can lead to:

1. Enhanced flight safety
2. Operational Efficiency
3. Stakeholder Confidence
4. Data Driven Decision Making

Risk Assessment Participants:

1. Ugyen Lhamo, Met officer
2. Sonam Phuntsho, Safety Manager
3. Sangay Tenzin, AIS officer
4. Karma Thinlay, CNS officer
5. Tshering Dorji, Met officer
6. Tshering Nima, Met Technician
7. Ten Dorji, ATC
8. Rinzin Samdrup, Met Technician

Sl No.	Hazard	Hazard Related Consequences	Existing Defenses to control Risks	Severity	Probability	Risk Score	Further action to reduce risk(s)	Severity	Likelihood	Residual Risk Score	Responsibility
1	Wind shear at PIA	Short/long landing leading to hard landing	Initiate go-around procedures with consent from Pilots	D	4	4D	Wind Shear Warnings and Alerts.	D	3	3D	NCHM, Airlines, DoAT BCAA
		Runway excursion leading to crash	Initiate go-around procedures with consent from Pilots -Wind Curfew	A	3	3A	-Wind Shear Warnings and Alerts -RESA	A	2	2A	NCHM DoAT Airlines BCAA
		Damage to Landing Gear	Initiate go-around procedures with consent from Pilots	C	3	3C	-Wind Shear Warnings and Alerts	C	2	2C	NCHM Airlines DoAT

Conclusion

This comprehensive Wind Shear Assessment Report for Paro International Airport consists of an extensive analysis of meteorological data, pilot and ANSD feedback , and safety risk evaluations to address the critical issue of wind shear and its implications for aviation safety. This report integrates multiple data sources, including five years of AWOS data, analysis of RWP data, pilot insights from survey questionnaires, and rigorous safety risk assessment conducted in collaboration with key stakeholders such as BCAA, DoAT and NCHM.

The analysis of AWOS data revealed consistent temporal patterns of wind shear, with a particular focus on horizontal shear. Utilizing component and vector analysis, the data identified multiple occurrences of shear magnitudes exceeding the ICAO-recommended 15-knot threshold, posing a potential hazard to aircraft during critical flight phases. The RWP data, though limited to several months, confirmed the presence of vertical wind shear across different altitudes, with significant risks identified below 2000 feet, where aircraft are most vulnerable during takeoff and landing. This reinforces the need for ongoing wind shear monitoring, particularly in the 500–1500 feet altitude range, where shear magnitudes consistently reach hazardous levels.

In addition to the quantitative meteorological data, pilot surveys provided valuable qualitative insights into the challenges posed by wind shear at Paro International Airport. Pilots consistently highlighted difficulties encountered due to sudden changes in wind direction and speed, corroborating the findings from AWOS and RWP data analyses. These real-world observations from those directly involved in daily operations lend weight to the conclusions drawn from the data.

The safety risk assessments, conducted by SMS liaison officers from BCAA, DoAT, and NCHM, provided a thorough evaluation of the safety implications of wind shear. These assessments were crucial in identifying operational vulnerabilities, developing mitigation strategies, and ensuring compliance with ICAO standards.

Overall, this report confirms that wind shear is a persistent and significant operational challenge at Paro International Airport, particularly due to its unique geographical and meteorological conditions. The findings emphasize the need for continuous wind shear monitoring, effective mitigation strategies, and robust risk management protocols to ensure flight safety.