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CRITICAL FACTORS OF AIR TRAFFIC CONTROLLER METEOROLOGICAL AWARENESS AND AWOS OPTIMIZATION FOR WEATHER-INDUCED FLIGHT INCIDENTS MITIGATION IN LOW LEVEL FLIGHT PHASES

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Abstract: Meteorological-induced aviation incidents in Indonesia have become a main concern in recent decades. To mitigate this risk, an in-depth understanding is required, especially related to factors that contribute to incident mitigation. From a meteorological perspective, the primary concern is the sufficiency of instruments that provide accurate information, which should be made available promptly. Hence, instrument and human factors are important to mitigate these incidents. Despite its urgency, to the best of the authors' knowledge, there is a lack of studies that studied both factors and interactions related to weather-induced flight incidents in Indonesia. The objective of this research is to analyse the incidents and evaluate possible improvements to be implemented to increase flight safety in Indonesia, especially from meteorological and ATC perspectives. A Literature study method was used for this work based on past investigation reports conducted by the Indonesian National Transportation Safety Board using 122 flight incident reports from 2020-2025 as a source of data. Based on the conducted analysis, low-level flight phases are more prone to incidents due to human factors and low-level weather phenomena such as wind shear. Therefore, it is proposed to conduct a novel ATC meteorological training program with a main focus on impact-based and real-world cases using ground class and full flight simulations and AWOS optimisation for wind shear early warning detection. By optimising existing AWOS located in various airports as an early alternative to LLWAS, Indonesia could save more than 2.1 trillion IDR and increase the safety level of aviation using wind shear warning from AWOS instruments supported by sufficient ATC capabilities from the training program.

Keywords: Flight Safety, Wind Shear, Flight Training, Incident Analysis, Weather-Induced Incidents.

Introduction

The safety aspect in aviation has been a critical issue since the first era of modern aviation. With continuously improving technology and a regulatory framework, the resulting safety risks have also become more complex and are affected by multidisciplinary causes. Indonesia, as an archipelagic country with diverse geographical conditions, is not an exception to various imposed safety and service risks in air transport (Ramadhani et al., 2024). Moreover, this risk becomes higher for remote and hardly accessible areas in mountainous regions such as in

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Papua (Kameswara & Suryani, 2021). Besides, meteorological conditions are already known as one of the leading factors in flight safety incidents (FAA Aviation Safety, 2022).

Based on a previous study, meteorological conditions affect safety during flight operations. This is especially true for low altitude and critical phases such as approach and climbing, which are accompanied by low-level down draft, cumulonimbus, thunderstorm, and low visibility (Megi et al., 2025). In such a critical condition where low-level meteorological phenomena occur, restricted reaction time is available, making it crucial to act accordingly. According to statistical data, approximately 56% of commercial jet accidents occur during the approach and landing phases, highlighting the vulnerability of aircraft in this configuration (Boeing, 2024). In low-level operational conditions, such as approach and climbing, these incidents are mainly caused by wind shear. Wind shear is an abrupt and sudden change in wind speed and direction. In terms of aerodynamics, this abrupt wind direction and velocity change will cause aircraft loss of lift, down draft, and unstable control, which results in incidents and accidents such as aircraft crash, unstable control, controlled flight into terrain (CFIT), and runway excursion. US Air Flight 1016 was one of the known examples of how heavy thunderstorms and microburst-induced windshear could induce a catastrophic accident, as the crash and ensuing fire caused 37 fatalities and seriously injured 20 others (NTSB 1994 US Air, n.d.). Ratnasari (Ratnasari et al., 2022) studied the effect of extreme wind shear in Soekarno International Airport, the busiest airport in Indonesia, which caused traffic problems, go-around, and diversion of several jet aircraft.

In its implementation, aviation meteorological condition is informed by the Air Traffic Controller to the pilot during flight operation (ICAO Doc 8896 Manual of Aeronautical Meteorological Practice, 2019). Thus, to reach higher safety aspects, meteorological information should be accurate, correctly interpreted, and delivered in a timely manner. To achieve this, Air Traffic Controllers should have sufficient knowledge and competency to support their role and communication with pilots regarding the meteorological information. However, mere transmission of data is not enough as the controller must possess "situational awareness", which involves perceiving the weather elements, comprehending their meaning, and projecting their status in the near future (Endsley, 1995).

Several works have been conducted to improve the aviation meteorological information for flight operations. More sophisticated meteorological instruments, such as the Low-Level Windshear Alert System (LLWAS), are already implemented as early prevention to wind shear phenomena in airports. Gultepe et al. (Gultepe et al., 2019) stated that automated sensors are critical for providing high-frequency data updates required to detect transient hazards like microbursts. However, the effectiveness of this technology depends on the human operator's trust and understanding. Yen & Chen ((Yen & Chen, 2017) highlighted that human factors in the design of wind shear alerting systems are crucial, as misinterpretation can lead to delayed warnings. However, to the best of the authors' knowledge, there is a lack of papers that correlate the importance of ATC knowledge and competencies with existing airport meteorological instruments in increasing the flight safety aspect, especially in low altitude operation, in which the airport weather instruments become crucial. Therefore, to fill the knowledge gap, this paper discusses the critical factors of ATC awareness and existing meteorological instruments to be optimised in increasing the level of safety and mitigating aviation safety incidents, which could be caused by meteorological factors.

Therefore, the research problems addressed in this study are:

1. What are the critical factors of ATC meteorological awareness required for safe operations, especially during low level flight phase?

2. What methods can be proposed to improve a higher level of safety due to meteorological and wind shear-induced flight incidents?

Method

This work implemented a literature review and qualitative analysis method. Thematic analysis was done using incident investigation reports to evaluate the flight incidents and their root cause in Indonesia ranging from 2020 to 2025. 122 incident occurrences from 2020-2025 are used. As a note, only incidents in civil aviation category are studied based on scope of role of Indonesian NTSC. Besides, only serious incidents and accidents are used for the data sample considering their severity to aircraft, environments, and injuries to people. Using thematic analysis, the impact, root cause, and safety recommendations of each incident are evaluated. Each root cause and recommendations are categorized based on relevant keywords.

Procedurally, the first step of this research is to collect relevant flight incident investigation reports from Komite Nasional Keselamatan Transportasi. After the investigation data has been collected, the type of incidents for each occurrence is categorised. The severity and impact of incidents are determined from damage to aircraft and environment, number of injuries and fatalities, and classification of serious incidents and accidents terminologies stated by the International Civil Aviation Organisation (ICAO). An accident is a type of incident that causes serious injuries, fatalities, or severe aircraft damage. On the other hand, a serious incident is a type of incident that involves circumstances that indicate a high probability of accidents (International Civil Aviation Organization, 2020). After the analysis has been conducted, the root causes of flight incidents are categorised into five distinct categories: Pilot/Human Factors, Meteorology/Environmental Factors, Air Traffic Controller (ATC) & Communication, Technical/Aircraft Factors, and Runway/Aerodrome Factors. To categorise the factors, a strict analytical framework is applied. Pilot/Human Factors are categorised when errors occur in handling or decision making despite the aircraft functioning normally. On the other hand, Technical/Aircraft Factors are categorised when there are hardware or software malfunctions which are largely outside the control of the crew. Additionally, ATC & Communication factors are identified based on monitoring latency and coordination failures. After the root cause of each incident has been categorized, the recommendations based on KNKT report is evaluated to find the most critical factors and propose the most effective solutions to solve the weather-induced flight incidents.

Discussion

1. Analysis of Flight Safety Incidents

From conducted analyses, 71 serious incidents and 51 accidents occurred from 2020 to 2025 as shown in Figure 1, while the number of injured people and fatalities of these incidents are provided in Figure 2.

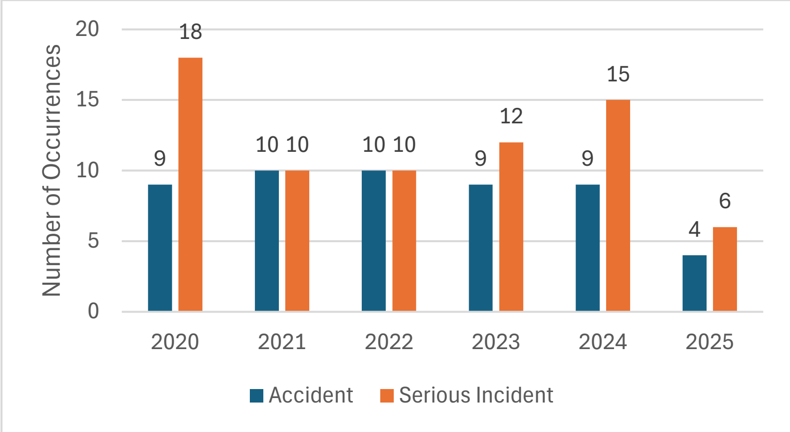

Figure 1. Number of Accidents and Serious Incidents on Year 2020 – 2025

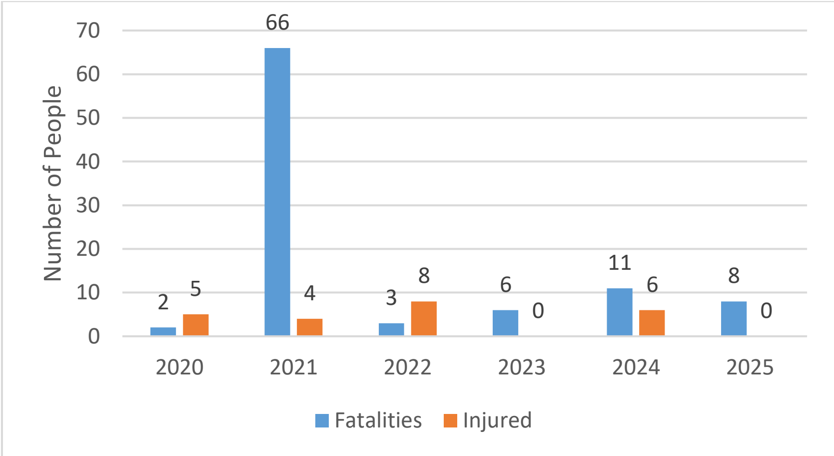

Figure 2. Number of Injured and Fatalities on Year 2020 – 2025

From Figure 1, it is seen that in general number of flight incidents decreased each year. This trend is also supported by the decrease in injuries and fatalities caused by flight incidents in Figure 2. However, the number of fatalities spiked significantly due to a loss-of-control accident that caused the deaths of 62 people on board (Komite Nasional Keselamatan Transportasi Republik Indonesia, 2022). Furthermore, these occurrences could be divided into 7 incident categories, with the proportion of occurrence relative to total occurrences shown in Figure 3.

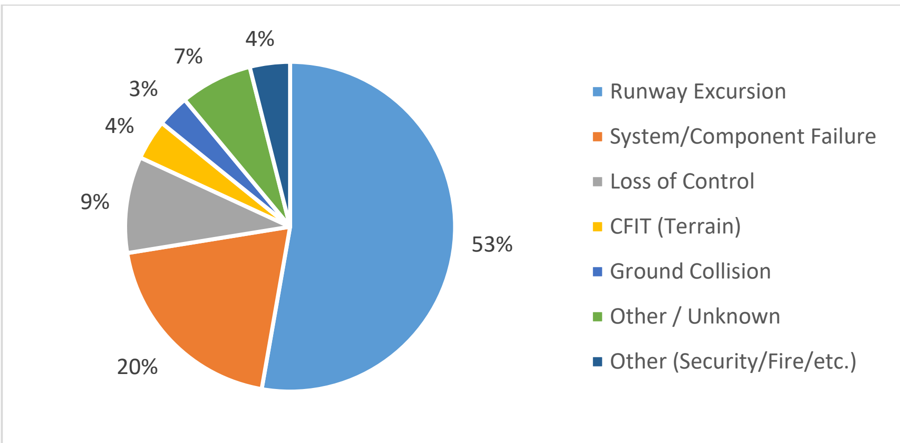

Figure 3. Flight Incidents Type Categorisation

Based on Figure 3, runway excursion is the most frequent incident with 53%. Runway excursion is defined as an incident that occurs when an aircraft veers off or overruns the runway surface during takeoff or landing (International Civil Aviation Organization, 2022) (Wang et al., 2024). This result agrees with the International Air Transport Association (IATA) report, which stated that runway excursions are the most frequent incidents in airport (IATA, 2022). On the other hand, despite its relatively low occurrence, Loss of Control In Flight has the highest fatality rate, with the deadliest accident with 62 fatalities involving Sriwijaya Air SJ182 in 2021, and the recent one was caused by a stall resulting in loss of control and 4 fatalities in SAM AIR in 2024. In addition, these flight incident data could also be categorised based on the flight phase, as seen in Figure 4.

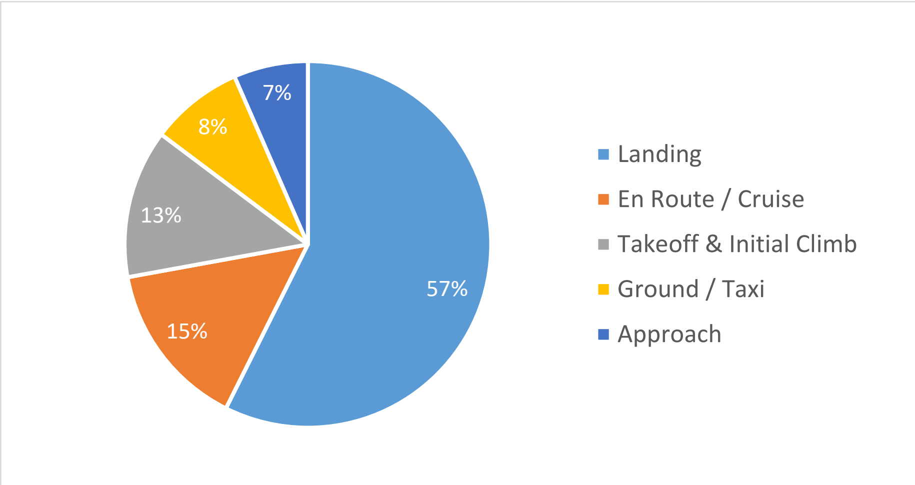

Figure 4. Flight Incidents Occurrence Based on Flight Phase

From Figure 4, most of the incidents occurred during landing. The incidents that occurred in this phase are mainly Runway Excursions (RE) and Hard Landings. This result supports previous research (Woodman et al., 2024)(Sheffield et al., 2025) and data in Figure 3 with runway excursions/incursions as the most frequent incidents in Indonesia. On the other hand, other incident types that occur during low altitude operations are Loss of Control due to stall, Controlled Flight into Terrain (CFIT) especially in mountainous area during approach, and rejected take off which also results in runway excursion.

Based on the comprehensive analysis of investigation reports(Komite Nasional Keselamatan Transportasi Republik Indonesia, 2025) , the primary contributing factors can be classified into five distinct categories: Pilot/Human Factors, Meteorology/Environmental Factors, Air Traffic Controller (ATC) & Communication, Technical/Aircraft Factors, and Runway/Aerodrome Factors. Pilot/Human Factors are related to the flight crew's cognitive and operational performance, encompassing decision-making processes, manual handling skills, and adherence to standard operating procedures (SOPs) under high-workload conditions. Meteorology/Environmental Factors pertain to atmospheric dynamics and external physical hazards, specifically focusing on critical phenomena such as low-level windshear, microbursts, precipitation intensity, and rapid visibility deterioration. Air Traffic Controller (ATC) & Communication refers to the systemic efficacy of traffic management, including the timeliness of hazard information dissemination, coordination between sectors, and the clarity of phraseology during critical flight phases. Technical/Aircraft Factors are associated with mechanical or avionic malfunctions internal to the aircraft, such as propulsion failures, landing gear anomalies, or instrument errors, which operate independently of the external environment. Runway/Aerodrome Factors relate to the physical condition and infrastructure of the landing interface, including surface friction coefficients (hydroplaning risks), drainage efficiency, and the operational status of visual aids. As a note, an incident might be caused by multiple factors that are intertwined.

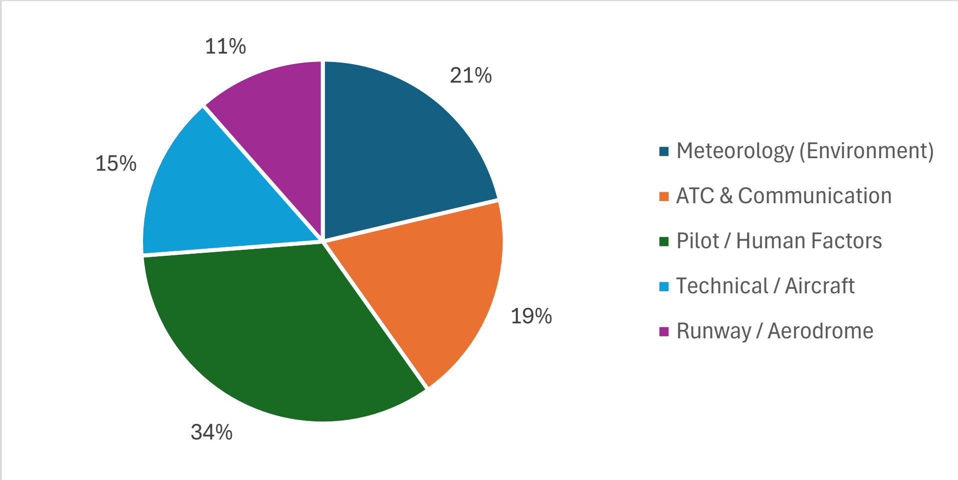

Figure 5. Percentage of Causing Factors of Flight Incidents

From the evaluated cause of incidents in Figure 5, meteorology and ATC & Communication factors combined account for 40% of all incidents. This validates this research focus on the interface between weather detection and controller awareness. In addition, pilot/human factors have 34% proportions as a cause of incidents (N=41). By referring to Figure 5, in which the most frequent incidents occurred in the landing phase, this human factor might be related to fatigue due to the accumulative workload, which correlates with handling and unstabilized approach (Silva et al., 2025) and spatial disorientation. On the other hand, meteorology (environmental factors) ranked second by contributing 21% (N=26) of total incidents. This category represents the physical root cause of the most severe incidents in the dataset. Unlike mechanical failures, which can often be managed, low-level meteorological phenomena present unrecoverable energy states for the aircraft. The specific phenomena identified include microbursts, wind shear, and rapid visibility deterioration. Furthermore, ATC & communication ranked third with 18.8% (N=23). Accounting for 23 incidents, this category highlights the critical role of the information loop between the ground and the air. The failure modes in this category were due to Monitoring and Alerting Failures (Detection Latency), indicated by the inability of the controller to perceive or react to a developing hazard in a timely manner. In addition, it is also caused by Coordination and Information Relay Failures and Phraseology and Readback/Hear back Errors.

Applying Endsley's Situational Awareness (SA) model to the analysed incident data reveals that high ATC workload precipitates a critical degradation in meteorological processing, effectively forcing a regression from predictive Level 3 (Projection) capabilities to basic Level 1 (Perception) (Endsley, 1995). The analysis indicates that while controllers frequently perceive raw weather data (Level 1), cognitive saturation during complex traffic scenarios hinders the Level 2 (Comprehension) required to integrate meteorological dynamics with aircraft performance limits, and the Level 3 (Projection) necessary to anticipate microburst outflows before they impact operations. Consequently, the prevalence of 'reactive' incidents—where hazards are identified only via Pilot Reports (PIREPs) rather than prior avoidance—demonstrates a systemic failure to project future states, highlighting the critical need for AWOS optimisations that convert raw sensor inputs into immediate impact assessments to sustain high-level SA under operational pressure.

On the other hand, Technical/aircraft error contributes 14.8% (N=18). These incidents are due to mechanical malfunctions independent of the environment, such as landing gear collapse, engine failures, or hydraulic leaks. Unlike meteorological hazards, which are dynamic and external, technical failures are often contained within the aircraft's internal systems. The remaining 14 incidents were attributed to infrastructure conditions. In the context of wet-weather operations, this primarily manifested as Hydroplaning due to poor runway drainage or rubber deposits lowering the friction coefficient. This factor is closely linked to Meteorology; a heavy rain event (Meteorology) becomes an incident only when combined with poor drainage (Aerodrome) or poor meteorological condition reports (Communication).

From evaluated data, it is evident that the low altitude flight phases are critical during flight operations, while human factors and environment play important roles in aviation safety incidents and accidents. Furthermore, the most severe incidents at low-level altitude that are related to human factors and environments are caused by low-level wind shear. Wind shear is a condition in which the wind direction and/or speed changes abruptly in a short time period, which mainly affects the aerodynamics and control of the flight vehicles. These incidents have a higher risk in mountainous area which are notable for their high and diverse elevation and prone to mountain waves that could induce abrupt changes in wind direction and wind speed. During low-level operation, the most critical roles are the flight crew, which operates the aircraft and ATC, which informs the weather conditions. Thus, it is mandatory to have proper knowledge, competencies, and correct utilizations into situational awareness and decision making to mitigate flight incidents that are caused by human factors and the environment.

II. Strategic Issues: The Gap of Meteorology and Air Traffic Control Service

Indonesian National Transportation Safety Board recommendation to Airnav Indonesia as the sole Indonesian Air Navigation Service Provider can be used to evaluate air traffic control critical factors and roles in mitigating aviation safety incidents. From the evaluated data, the recommendations are related to meteorology and windshear, airspace charts, airspace spatial understanding, communication, emergency handling, clearance (includes conditional clearance such as landing clearance), and aircraft movement in the manoeuvring area. These recommendations also support the importance of situational awareness for Air Traffic Controllers. Not only prominent and accurate spatial awareness are necessary, but ATC should also have sufficient meteorological knowledge and their impacts to airspace to support their roles (Endsley, 1995). Based on The Hierarchy of Control in Safety Engineering Method (Ajslev et al., 2022)(Federal Aviation Administration, 2022), the ranking of these factors from the first prioritised to the least prioritised is meteorology and windshear, communications (listen, readback, phraseology), airspace charts and spatial assurance, emergency handling, clearance, airspace 3-dimensional and temporal understanding, and aircraft movement in the manoeuvring area.

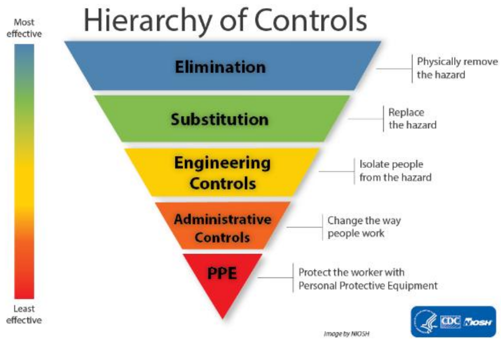

Figure 6. Hierarchy of Controls Diagram (NIOSH, 2024)

The prioritisation of meteorological enhancements over communication improvements is considered by the Hierarchy of Controls as seen in Figure 6. Hierarchy of Control is notable as a fundamental framework in systems engineering and occupational safety, as hazard control measures are ranked by effectiveness: Elimination, Substitution, Engineering Controls, Administrative Controls, and Personal Protection. Within the aviation safety context, severe meteorological phenomena such as windshear or microbursts represent an inevitable physical hazard. Accurate meteorological detection infrastructure combined with accurate and timely information allows for Hazard Elimination. Based on the analysed incident data, the related incidents to meteorology are provided in Table 1.

Table 1. Incidents related to Meteorology in Low Altitude Operation

Date	Operator	Aircraft	Location	Phase of Flight	Specific Phenomenon	Outcome & Severity
May-20	MAF	Quest Kodiak (PK-MEC)	Sentani (Papua)	Takeoff	**Microburst / Downdraft.** Encountered sinking air from a storm cell immediately after takeoff.	**FATAL.** Aircraft crashed into Lake Sentani.
Sep-21	Rimbun Air	Twin Otter (PK-OTW)	Intan Jaya (Papua)	Approach	**Mountain Wave / Downdraft.** Strong winds flowing over the ridge created a downdraft, pulling the aircraft into terrain.	**FATAL (CFIT).** Impacted ridge in fog/wind.
Feb-24	Smart Av	Caravan (PK-SNK)	Pogapa (Papua)	Landing (Flare)	**Variable Gusts.** Sudden wind gust during the flare caused a loss of lift and hard landing.	**Accident.** Runway excursion/Gear collapse.
Jun-25	Batik Air	Boeing 737-800	Jakarta (CGK)	Short Final	**LLWS (Low Level Wind Shear).** Severe crosswind shear caused uncommanded roll <500 ft.	**Serious Incident.** Recovery/Go-Around executed.
Dec-20	Lion Air	Boeing 737-900	Lampung (TKG)	Landing Roll	**Tailwind Shear & Heavy Rain.** Sudden tailwind component combined with hydroplaning.	**Accident.** Runway Excursion (Overran runway).
2021	Citilink	ATR 72	Bandung (BDO)	Landing	**Squall / Visibility.** Rapid deterioration of visibility and heavy rain during touchdown.	**Incident.** Runway Excursion (Veered off side).
2020-23	Wings Air	ATR 72	Various (Semarang)	Landing	**Crosswind Exceedance.** Landing attempts in gusty crosswinds exceeding aircraft limits.	**Incidents.** Tailstrikes / Hard Landings.
2021	Gen. Aviation	Bell 412 (Heli)	Papua (Highland)	Landing	**Downdraft.** Loss of effective translational lift due to sudden wind shift.	**Accident.** Hard landing/Rollover.

Based on Table 1, the incidents related to meteorology at low-level altitude are mainly due to aerodynamic factors such as down draft, gust, and cross wind. Down drafts occurred in three years during 2020-2025 period. This down draft mainly occurred as a consequence of wind shear and formed Cumulonimbus (CB). Gusts are also responsible as they influence the wind direction and induce unstable control, especially in critical conditions during low altitude flight. On the other hand, visibility minima are also deemed responsible for other incidents, especially during heavy rain conditions. Furthermore, the incidents related to meteorology dominantly occurred in mountainous areas in the Papua region, which emphasises the impact of mountainous regions on mountain waves, visibility issues, and local unpredictable weather, which lead to a higher risk of incidents in mountainous areas.

On its implementation, the aviation meteorology service and information in Indonesia are provided by the Indonesian Agency for Meteorology, Climatology and Geophysics (Badan Meteorologi Klimatologi dan Geofisika) (Indonesian Ministry of Transportation, 2018). ATC, which has responsibilities to communicate with pilot could relay the observed conditions using BMKG information.

Based on the analysed data and recommendations, critical issues in meteorology that affect the incidents are:

1. The gap of observation between meteorological facilities and instruments, ATC tower, and pilot observations.
   There are limitations and blind spots between the instrument sensor scope of effectiveness, ATC observation scope in the observation tower, and pilot observations in the cockpit. As some of the meteorological phenomena occur locally, such as Microburst or Downburst which are often localised and only 1–2 miles wide, there might be discrepancies between each observer. Thus, it is important to have proper and unified understanding of the meteorological phenomena and early indications that might occur. As a result, if ATC observes the indication of wind shear, ATC could confirm and inform BMKG and the pilot to give early mitigation.

2. Gap of knowledge and the necessity to shift the core paradigm and perspective from observation-based to impact-based syllabus
   Existing competencies in general aviation meteorology mainly focus on observation and data interpretation, such as normative decoding of aviation reports (such as METAR, TAF, and weather charts). On the other hand, in critical conditions, the decisions should be made based on the impact priority. Thus, in a dire situation, ATC should prioritise weather information based on its impact on safety.

III. Proposed Solutions to Leverage ATC Knowledge and Meteorological Instruments

According to the previously discussed critical issues, it is proposed to develop periodical training for ATC to improve their meteorological knowledge and awareness. The proposed training program is provided in Figure 6.

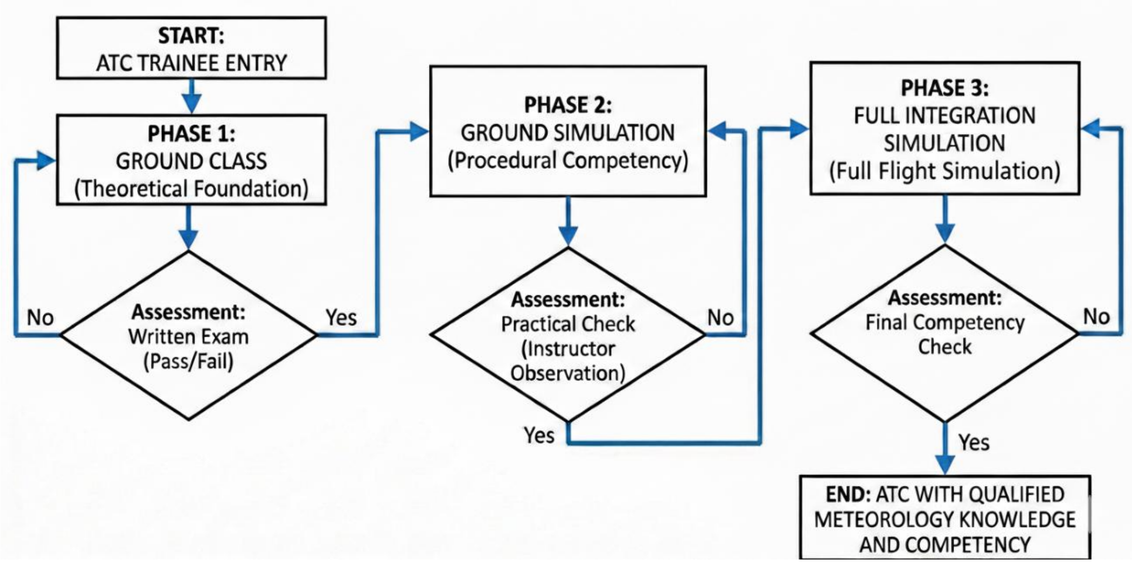

Figure 7. Proposed ATC Training Program

As seen on Figure 7, the training should include ground class, ground simulation, and 360 tower and cockpit full flight simulation. The ground class should include a sufficient theoretical basis and be backed up with practical, real-world cases. This module emphasises the physics of severe weather, specifically the lifecycle of Cumulonimbus (CB) formations and the aerodynamic impact of microbursts and windshear on aircraft performance. It also includes technical mastery of detection equipment, such as the Low-Level Wind Shear Alert System (LLWAS) and AWOS. After that, the trainee should be assessed through a written exam to evaluate their knowledge. The second phase of this training is ground simulation. In this case, the trainee should implement their knowledge through an oral test. This phase bridges the gap between static knowledge and dynamic procedure. Utilising part-task trainers or standard tower simulators, trainees practice applying Standard Operating Procedures (SOPs) in non-critical environments. The last phase of the training program is full integration simulation using the Full Flight Simulation (FFS) facility. In the last phase, ATC trainee awareness and empathy should be emphasized as they could observe the situation in the cockpit during windshear conditions. By introducing high-fidelity 6-axis cockpit simulation, ATC trainee is exposed to complex, high-workload scenarios that replicate the stress of real-world operations.

Based on the occurred incidents, there are critical factors that should be included in the syllabi:

1. Aviation Meteorology report decoding with visual representation and real-world cases to enhance ATC awareness.
   This should include any indication that should be prioritised, such as "CB" code in METAR, thunderstorm and heavy rain, and other significant meteorological reports and aerodrome warning (AD Warning)
2. Convective weather, microburst, and Cumulonimbus formation and indication based on observation and weather reports, as seen in mountainous flight incidents.
   Through visual observation, ATC could comprehend the lifecycle of a thunderstorm, which could be accompanied by microbursts.
3. Wind shear recognition and relevant instruments to detect them, based on Batik Air and Garuda Incidents.

Wind shear could occur locally and not be observed by BMKG, yet can be detected by instruments that can be read in ATC facilities, such as the Low Level Windshear Alert System (LLWAS) and the Automated Weather Observing System (AWOS). Sufficient knowledge in utilising visual observation and instruments could help ATC in detecting windshear. In addition, understanding what a pilot is performing during a windshear escape (such as full power, pitch up response) could help the controller know not to interrupt them with radio calls and increase the pilot workload.

4. Visibility and visual reference

   ATC should know the parameters of visibility minima. By referring to real world case study (such as the distance from the observer to a known landmark in certain airport), ATC could estimate the actual visibility.

In addition, other problems that arise in Indonesia are the limitation of weather instruments in several airports, which are especially true for isolated and small airports. With all of 606 civil airports and airstrips in Indonesia (Indonesian Directorate General of Civil Aviation, 2026), there are only 5 airports equipped with the Low Level Windshear Alert System (LLWAS). To solve this issue, it is proposed to optimise the utilisation of the Automated Weather Observing System (AWOS) as an alternative to enhance wind shear detection. Nevertheless, these AWOS are only used to read the wind direction and speed on runways. Given that windshear can be detected by evaluating the change in wind speed and direction within a certain period of time, AWOS can also be used to indicate low-level wind shear. Thus, it is proposed that knowledge on utilizing AWOS be included in the meteorological training program for ATC. Currently, there are 181 AWOS units in Indonesia. By optimising existing AWOS located in various airports rather than procuring more existing LLWAS, Indonesia could save more than 2.1 trillion IDR and increase the safety level of aviation using wind shear warning from AWOS instruments supported by ATC capabilities as seen in Figure 8.

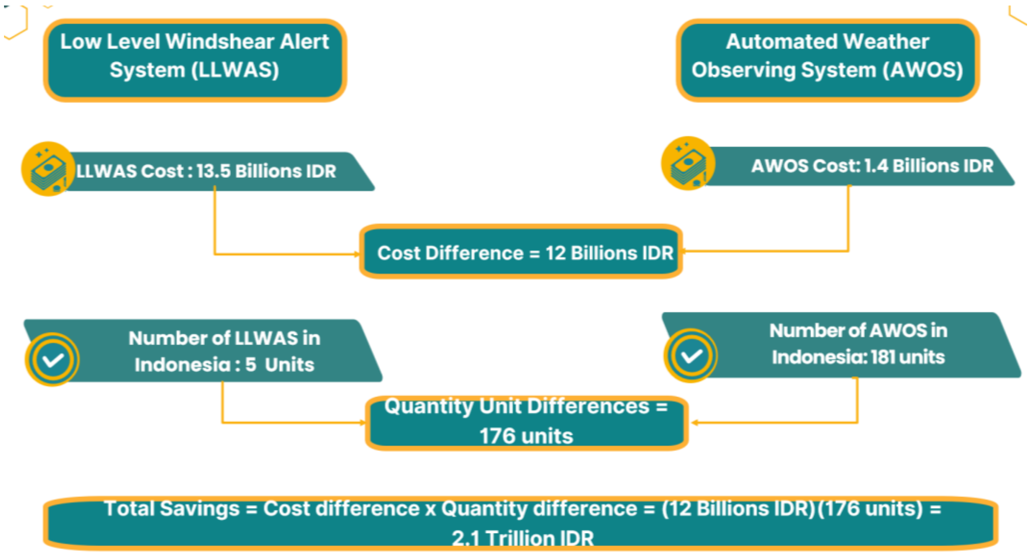

Figure 8. Proposed AWOS Instrument Optimisation to Increase Wind Shear Detection Capabilities in Airports

In addition, proper installation of sensors is required to optimise the utilisation of AWOS. To mitigate the meteorological "blind spots", a multi-sensor array is required. It is recommended to install anemometer components at three critical locations along the runway assembly, which are in the Touch Down Zone (TDZ), Mid-Point (MID), and Stop-End (END). Placement in TDZ is essential for detecting headwind/tailwind shifts during the landing flare, while placement in MID is required for runways >2000m to monitor crosswind components during rollout. Furthermore, placement in the Stop End is essential to support reciprocal runway operations and detect gust fronts moving across the airfield (International Civil Aviation Organization, 2018).

Conclusion

From the conducted analysis of flight incidents and accidents in Indonesia, it is known that low-level flight phases are critical to safety risks. This is highlighted with Runway Excursion as the most common type of occurrences, with low-level wind shear indication as the main contributor to severe flight incidents. After thorough analysis, the environment (meteorological) and ATC & Communication combined have a large proportion of causes for these incidents. To solve these issues, a novel ATC meteorological training program and AWOS optimisation for wind shear early warning detection are proposed. The training is proposed to include ground class, ground simulation, and cockpit full flight simulation. In addition, AWOS optimisation for wind shear warning is proposed. By optimising existing AWOS located in various airports as an early alternative for LLWAS, Indonesia could save more than 2.1 trillion IDR and increase the safety level of aviation using wind shear warning from AWOS instrument supported by ATC capabilities (Tim Kajian Kantor Otoritas Bandar Udara Wilayah VI - Padang, 2023). It is recommended that the DGCA develop a regulatory framework for the proposed 'Three-Phase Meteorology Competency Framework'. Crucially, AirNav Indonesia must also implement this framework not only as an initial certification requirement but as a mandatory periodic refresher program (e.g., occurring biannually). Furthermore, it is also recommended that the Indonesian Aviation Meteorological Stakeholder (BMKG) support the meteorological training for ATC and assist in optimising the utilisation of existing AWOS as an early alternative for weather observation instruments, especially for wind shear phenomena, which has higher impact on weather-induced flight incidents.

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