ISSN (Print) : 2337-9030 ISSN (Online) : 2685-2608
PILLAR OF PHYSICS
JURNAL BERKALA ILMIAH FISIKA
Vol. 19 (2), 2026, page. 118-125
DOI : https://doi.org/10.24036/n2yc9649

DYNAMIC FORCING OF A THUNDERSTORM UNDER WEAK THERMODYNAMIC INSTABILITY: AN INTEGRATED ANALYSIS USING UPPER-AIR OBSERVATIONS AND WEATHER RADAR AT KUALANAMU INTERNATIONAL AIRPORT

Reinal Taruna Wahyu Halawa[1*], Sabam Mikhael Simangunsong[1], Yosafat Donni Haryanto[1]

[1] *Department of Meteorology, Sekolah Tinggi Meteorologi Klimatologi dan Geofisika, Jl. Meteorologi No. 5 Tangerang 15119, Indonesia*
Corresponding author. Email: reinaltaruna.25@gmail.com

ABSTRACT

A thunderstorm event occurred over Kualanamu Airport on 3 May 2025 despite relatively stable thermodynamic conditions. This study aims to analyze the characteristics and triggering mechanisms of the storm using upper-air observations and weather radar data. Radiosonde parameters indicated weak atmospheric instability, with a Convective Available Potential Energy (CAPE) of only 15 J kg^{-1} and a non-negative Lifted Index (LI). However, the atmosphere contained abundant low-level moisture, as indicated by a precipitable water value of 52.3 mm and a low lifting condensation level (LCL) of approximately 220 m. Weather radar products (CMAX and CAPPI) revealed high reflectivity exceeding 60 dBZ, while VCUT analysis showed vertical cloud development reaching 5–6 km. In addition, Upper Wind Tracking (UWT) identified wind convergence around the 1,000 m layer, accompanied by veering and backing wind patterns that indicated alternating warm and cold advection. The results demonstrate that the thunderstorm was primarily triggered by dynamic forcing mechanisms, including low-level wind convergence and warm advection, rather than by strong thermodynamic instability. These findings confirm that organized convective systems can develop under thermally stable conditions when sufficient moisture and mechanical lifting are present, potentially producing heavy rainfall, lightning, and short-term disruptions to airport operations. The study also highlights the importance of integrating upper-air observations with weather radar analysis for identifying dynamically forced convection, thereby supporting aviation weather monitoring and short-term operational forecasting.

Keywords : Thunderstorm; Convective systems; Weather radar; Upper-air observations

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I. INTRODUCTION

Kualanamu International Airport, located in Deli Serdang, North Sumatra, is one of Indonesia's major aviation hubs and serves as the primary gateway to the western region of the country. Established to replace the former Polonia Airport, it was designed to support regional economic growth through modern transportation infrastructure and the development of an integrated aerotropolis area [1][2]. As a strategic transportation node, maintaining safe and efficient flight operations at Kualanamu is of considerable importance for both passenger mobility and logistics services.

Meteorological conditions play a critical role in aviation safety. Weather phenomena such as reduced visibility, heavy rainfall, strong winds, and thunderstorms can significantly disrupt airport operations, particularly during aircraft take-off and landing phases [3]. Among these hazards, thunderstorms associated with cumulonimbus (Cb) clouds are especially dangerous because they may generate intense precipitation, lightning, turbulence, downdrafts, and low-level wind shear. Consequently, continuous weather monitoring and the

Submitted: 07-06-2026 Accepted: 31-10-2026 Published: 31-10-2026

integration of real-time meteorological information have become essential components of airport operational management and aviation early warning systems [4].

Weather radar and upper-air observations are widely used to investigate the development of convective storms. Previous studies around Kualanamu International Airport have reported that convective systems, including squall lines, frequently produce hazardous weather conditions characterized by strong winds and significant radar reflectivity signatures. In addition, satellite observations and pilot reports have demonstrated that severe aviation weather events are often closely associated with the presence of deep cumulonimbus clouds in the vicinity of airport operations [5][6]. Atmospheric stability indices such as the Lifted Index (LI) and K-Index (KI) have also been shown to provide useful guidance for forecasting thunderstorms and severe convective weather [7].

However, most conventional forecasting approaches assume that thunderstorms primarily develop under conditions of strong thermodynamic instability, typically characterized by high Convective Available Potential Energy (CAPE) and negative Lifted Index values. In tropical regions, this assumption is not always valid. Several convective events have been reported to occur under relatively stable thermodynamic conditions, suggesting that dynamic forcing mechanisms, such as low-level wind convergence, warm air advection, vertical wind shear, and mesoscale lifting processes, may play a dominant role in initiating and sustaining convection. Despite their operational importance, the interactions between thermodynamic stability and dynamic forcing remain insufficiently documented, particularly in tropical airport environments [8].

This knowledge gap is particularly relevant for aviation meteorology because severe convective weather may develop even when conventional instability parameters indicate a low probability of thunderstorm formation. Reliance solely on thermodynamic indices may therefore lead to underestimation of hazardous weather conditions and reduce the effectiveness of operational forecasting and early warning systems.

Accordingly, this study aims to investigate the meteorological characteristics and triggering mechanisms of a thunderstorm event over Kualanamu International Airport through an integrated analysis of upper-air observations and weather radar data. The analysis combines weather radar products, including Constant Altitude Plan Position Indicator (CAPPI), Column Maximum (CMAX), Upper Wind Tracking (UWT), and Vertical Cut (VCUT), with surface observations, atmospheric sounding data, and instability parameters such as Convective Available Potential Energy (CAPE) and Lifted Index (LI). The objective is to identify the relative contributions of thermodynamic and dynamic atmospheric processes to the development of the observed convective system [5][6].

The findings of this study are expected to improve the understanding of dynamically forced convection in tropical regions and demonstrate the importance of integrating upper-air observations with weather radar analysis for aviation weather monitoring. Furthermore, the results may contribute to the enhancement of radar-based early warning systems and support operational decision-making for airport authorities and air navigation service providers in mitigating weather-related aviation hazards.

II. METHOD

This study employed a descriptive quantitative approach to investigate the thunderstorm event that occurred around Kualanamu International Airport on 3 May 2025 at 11:20 UTC. An integrated analysis was conducted by combining upper-air observations and weather radar data to characterize the thermodynamic and dynamic atmospheric conditions associated with the event.

Upper-air observations were obtained from routine radiosonde soundings conducted by the Kualanamu Meteorological Station. The sounding data provided vertical profiles of air temperature, humidity, wind speed, and wind direction throughout the atmosphere. These observations were further used to derive several atmospheric stability parameters, including Convective Available Potential Energy (CAPE), Lifted Index (LI), K-Index (KI), and vertical wind shear. These parameters were analyzed to evaluate the degree of atmospheric instability and the potential for convective cloud development.

Weather radar observations were acquired from the Kualanamu Meteorological Station using three-dimensional volumetric radar scans. The radar data were processed using the Rainbow software package to generate several radar products commonly employed in convective storm analysis. The products included:

1) *Column Maximum Reflectivity (CMAX)*, which represents the maximum radar reflectivity throughout the vertical column and was used to identify the most intense convective cells.

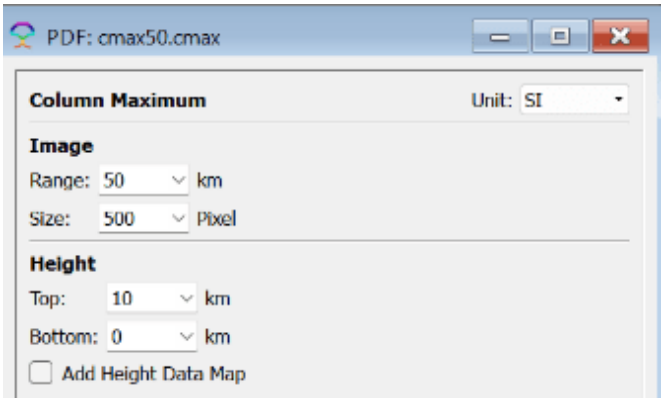

Fig. 1. CMAX Setting

2) *Constant Altitude Plan Position Indicator (CAPPI)*, which provides the horizontal distribution of radar reflectivity at a constant altitude and was used to examine the spatial structure of convective clouds.

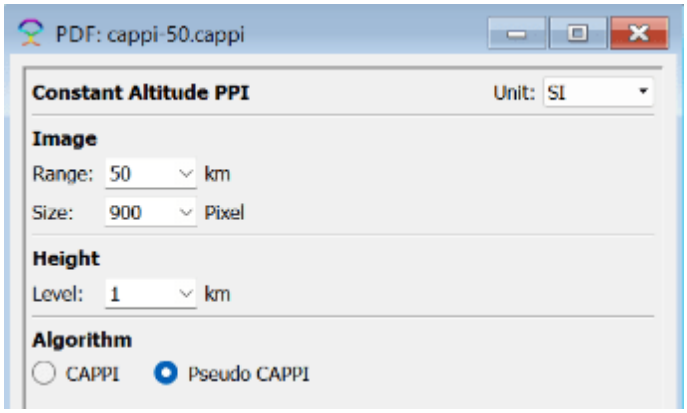

Fig. 2. CAPPI Product Setting

3*) Upper Wind Tracking (UWT)*, which was utilized to identify wind convergence and atmospheric flow patterns associated with convective development.

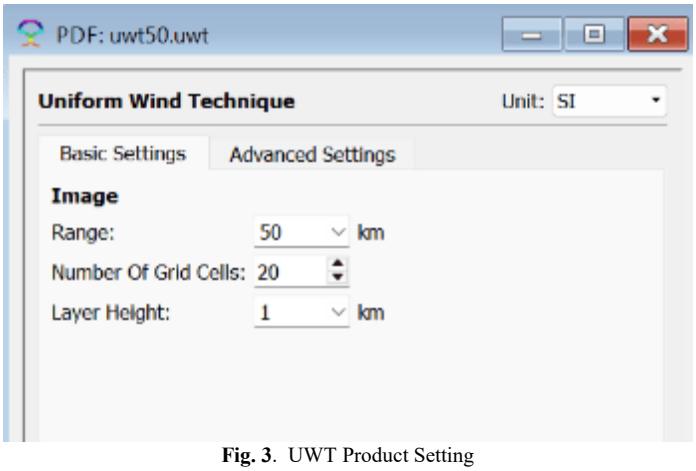

Fig. 3. UWT Product Setting

4) *Vertical Cross Section (VCUT)*, which provides a vertical profile of the radar echoes and was used to analyze cloud depth, vertical growth, and the internal structure of cumulonimbus clouds.

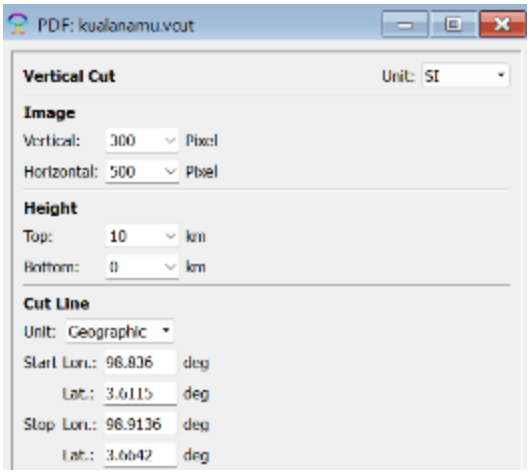

Fig. 4. VCUT Product Setting

The integrated analysis of sounding and radar observations was performed to examine the relationship between atmospheric thermodynamic conditions and dynamic forcing mechanisms during the thunderstorm event. Particular attention was given to identifying the roles of low-level moisture, atmospheric instability, wind convergence, and vertical cloud development in initiating and sustaining convection.

The overall methodological framework is expected to provide a comprehensive understanding of the atmospheric processes responsible for severe convective weather around Kualanamu International Airport and to support the improvement of aviation weather monitoring and early warning systems.

III. RESULTS AND DISCUSSION

The upper-air observations obtained from the radiosonde launch at 00:00 UTC on 3 May 2025 indicate that the atmospheric conditions around Kualanamu International Airport were relatively stable from a thermodynamic perspective. The Skew-T Log-P diagram presented in Figure 5 suggests a limited potential for thunderstorm development and severe convective activity. Although the radiosonde balloon burst before reaching the upper troposphere, the available observations were sufficient to characterize the lower- and mid-level atmospheric conditions relevant to convective initiation.

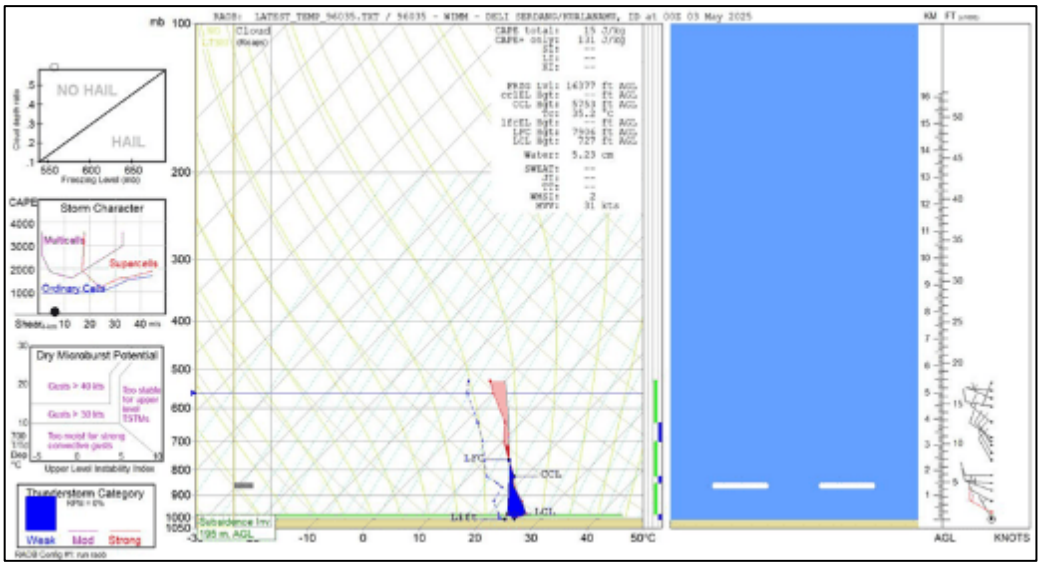

Fig. 5. Skew-T Log-P Diagram

A summary of the principal upper-air parameters is presented in Table 1. The sounding analysis indicates weak convective potential, as reflected by the low CAPE value, while the Lifted Index (LI) could not be determined because of the incomplete upper-air profile. In addition, the observed vertical wind field was relatively weak,

suggesting limited vertical wind shear. Under normal circumstances, these conditions would imply a low probability of deep convective development.

Table 1. Summary of upper-air and atmospheric parameters during the thunderstorm event

Parameter	Value	Interpretation
CAPE	15 J kg^{-1}	Weak convective energy
Lifted Index (LI)	Not identified	Incomplete upper-air profile
Precipitable Water	52.3 mm	High atmospheric moisture
LCL	220 m	Low cloud base
Vertical wind profile	5–15 kt	Weak vertical wind field
Warm and cold advection	Observed	Active atmospheric dynamics

Despite the weak thermodynamic instability, the lower atmosphere remained favorable for cloud formation. The relatively high precipitable water content and the low lifting condensation level indicate abundant low-level moisture. Furthermore, pilot balloon observations summarized in Table 2 revealed alternating warm and cold advection within the atmospheric column. Alternating warm and cold advection indicates active atmospheric dynamics and contributes to mechanical lifting, suggesting that atmospheric forcing processes were still active during the observation period.

Table 2. Pilot balloon observations

No.	Height (m)	Direction (°)	Speed (kt)	U	V	V/B	Adveksi
0	0	340	7	2.39	-6.58		
1	3000	295	8	7.25	-3.38	backing	Cold Advection
2	5000	270	10	10.0	0.0	backing	Cold Advection
3	7000	275	11	10.96	-0.96	veering	Warm Advection
4	8000	280	10	9.85	-1.74	veering	Warm Advection
5	9000	255	12	11.59	3.11	backing	Cold Advection
6	10000	280	9	8.86	-1.56	veering	Warm Advection

In contrast to the upper-air observations, the weather radar products revealed the existence of a well-developed convective system over the airport area. A summary of the radar-derived parameters is provided in Table 3. The CMAX product shown in Figure 5 recorded maximum reflectivity values exceeding 60 dBZ, indicating intense convective precipitation over Kualanamu International Airport. This interpretation is further supported by the CAPPI product (Figure 6), which confirms the horizontal distribution of high reflectivity associated with the convective cells.

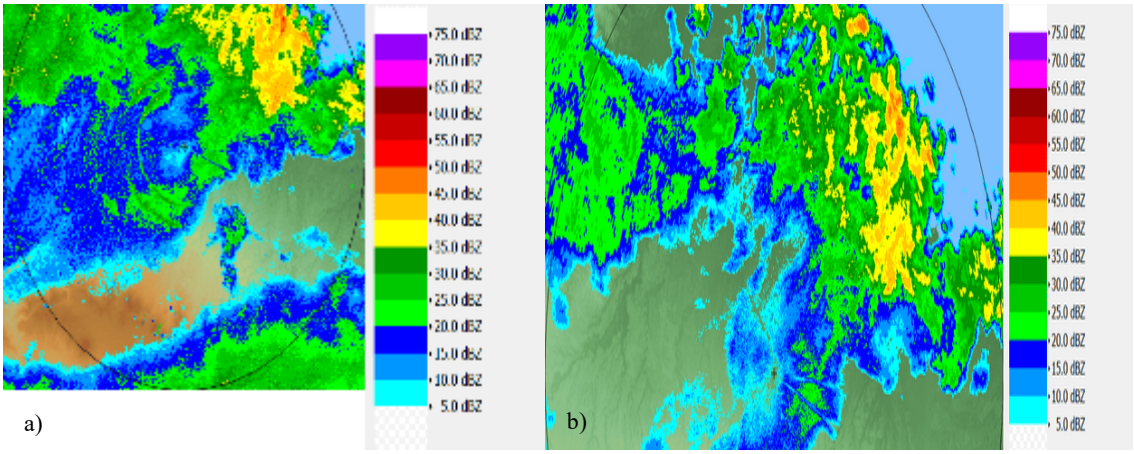

Fig. 6. a) CMAX product and b) CAPPI product image at 11.20 UTC

The vertical structure of the storm is illustrated by the VCUT product in Figure 7. The radar cross-section indicates that the convective cloud extended from a cloud base of approximately 2 km to a cloud top approaching 8 km, demonstrating the presence of a deep convective system capable of producing hazardous weather conditions. In addition, the UWT product (Figure 8) reveals a distinct low-level wind convergence pattern with maximum wind speeds ranging from 25 to 30 knots. The convergence zone likely served as the primary triggering mechanism for upward motion and cloud development.

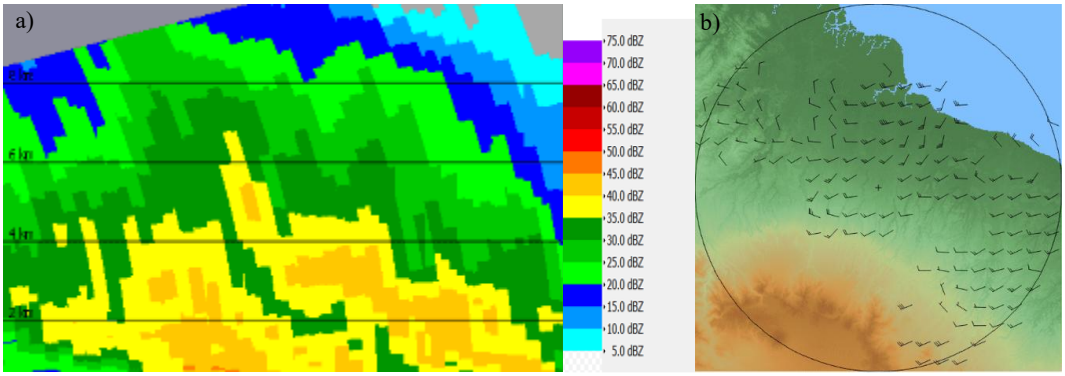

Fig. 7. a) VCUT product and b) UWT product image at 11.20 UTC

Table 3. Summary of weather radar observations

Radar product	Main finding
CMAX	Reflectivity >60 dBZ
CAPPI	High horizontal reflectivity over airport area
VCUT	Cloud depth from ~2 km to ~8 km
UWT	Low-level wind convergence
Maximum wind speed	25–30 kt

The comparison between the upper-air observations and the weather radar analysis reveals an apparent discrepancy between the thermodynamic and dynamic characteristics of the atmosphere. While the parameters summarized in Table 2 suggest a relatively stable atmospheric environment with limited convective energy, the radar observations summarized in Table 3 clearly indicate the presence of an organized thunderstorm system characterized by strong reflectivity, significant vertical cloud growth, and active low-level wind convergence.

These findings suggest that the thunderstorm was not primarily governed by buoyancy-driven free convection but was instead initiated and sustained by dynamic forcing mechanisms. The combination of abundant low-level moisture, a low cloud base, alternating warm and cold advection, and low-level wind convergence provided sufficient mechanical lifting to overcome the weak thermodynamic instability. Consequently, a deep convective system was able to develop even though the conventional instability indices did not indicate a high probability of thunderstorm formation.

This case study demonstrates that conventional thermodynamic parameters alone may not adequately represent thunderstorm potential in tropical environments. Dependence solely on atmospheric instability indices may therefore underestimate the risk of hazardous weather for aviation operations. The integration of upper-air observations and weather radar products provides a more comprehensive understanding of dynamically forced convection and offers valuable support for aviation weather monitoring, early warning systems, and short-term operational forecasting around Kualanamu International Airport.

IV. CONCLUSION

This study investigated the thunderstorm event that occurred around Kualanamu International Airport on 3 May 2025 through an integrated analysis of upper-air observations and weather radar data. The upper-air sounding indicated relatively weak thermodynamic instability, as reflected by the low Convective Available Potential Energy (CAPE) value of 15 J kg^{-1}, while the Lifted Index (LI) could not be determined because of the incomplete upper-air profile. Nevertheless, the atmosphere contained abundant low-level moisture, characterized by a precipitable water value of 52.3 mm and a low lifting condensation level (LCL) of approximately 220 m.

In contrast to the sounding analysis, weather radar observations revealed the presence of a well-developed convective system. Radar products showed reflectivity values exceeding 60 dBZ, vertical cloud development reaching approximately 8 km, and a distinct low-level wind convergence pattern with maximum wind speeds of 25–30 knots. The pilot balloon observations further identified alternating warm and cold advection, indicating active atmospheric dynamics that contributed to mechanical lifting.

The integrated interpretation of these observations suggests that the thunderstorm was not primarily driven by strong thermodynamic instability but was instead initiated and maintained by dynamic forcing mechanisms. The combination of high low-level moisture, a low cloud base, active advection, and low-level wind convergence provided sufficient lifting to support deep convection despite the limited convective energy indicated by conventional instability parameters.

The findings highlight that reliance solely on thermodynamic indices may underestimate thunderstorm potential in tropical environments, particularly for aviation weather forecasting. Integrating upper-air observations with weather radar products provides a more comprehensive approach for identifying dynamically forced convection and may enhance early warning systems, short-term operational forecasting, and weather-related risk mitigation for airport operations.

ACKNOWLEDGMENT

Please write a thank you note in this section. Gratitude is addressed to research funders or parties who contributed to the implementation of research or writing articles, other than the author.

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