JURNAL ILMIAH BERKALA SAINS DAN TERAPAN KIMIA
Jurnal Ilmiah Berkala: Sains dan Terapan Kimia
Vol. 20 No. 1, January 2026

Analysis of Atmospheric Vertical Structure During Hail in Tangerang: A Comparative Study of ECMWF Model Data and Radiosonde Observations

Analisis Struktur Vertikal Atmosfer Saat Hujan Es Di Tangerang: Studi Komparasi Data Model ECMWF dan Observasi Radiosonde

Dhanu Prakoso[1*], Aries Kristianto[1]

[1]Program Studi Meteorologi, Sekolah Tinggi Meteorologi Klimatologi dan Geofisika, Jalan Meteorologi 5 Tanah Tinggi, Tangerang, 15221, Indonesia

Email: dhanuprakoso07@gmail.com

ABSTRACT

Hail is an extreme weather event in tropical regions with local characteristics, short duration, and difficult to predict precisely. The hail event in Tangerang on October 31, 2025, is an important anomaly to study in order to understand the atmospheric structure that triggers massive instability in urban areas. This study aims to identify the vertical conditions of the atmosphere through a comparative study between global numerical model data from the European Centre for Medium-Range Weather Forecasts (ECMWF) and in-situ Radiosonde observation data. The methodology used is a case study approach by integrating remote sensing data from the Himawari-9 Satellite and C-Band Weather Radar to validate the structure of storm cells. Thermodynamic parameters such as Convective Available Potential Energy (CAPE) and freezing level profiles are extracted using Python programming to evaluate the model's ability to represent atmospheric lability conditions. The research results show a "wet bias" in the model data, indicating that the model is more humid than actual conditions.

Keywords Hail; radar; radiosonde; ECMWF

Received: 22 December 2025 ; **Accepted**: 23 January 2026: **Available online**: 29 January 2026

1. INTRODUCTION

Indonesia, as an archipelagic country located in the equatorial region, has unique weather characteristics with intense solar heating throughout the year. One of the extreme weather phenomena that often occurs during the transition period (*pancaroba*) in this region is hail. By definition, hail is a form of precipitation consisting of balls or irregular lumps of ice, caused by strong convective systems with updrafts exceeding the terminal velocity of ice particles (Knight & Knight, 2001). Unlike in mid-latitudes, the high freezing level in the tropics (typically > 4.5 km) acts as a deep melting layer, implying that only storms with intense updrafts and large initial hailstones can produce surface hail (Taszarek et al., 2021).

Hailstorms in the tropics are often very localized, short-lived, and challenging to

predict. The formation of hail requires specific atmospheric ingredients, namely significant conditional instability, sufficient moisture, and a favorable freezing level height that allows ice to reach the surface before melting. In tropical environments, these storms are typically driven by convective systems with vigorous updrafts capable of supporting heavy hydrometeors. Recent observations indicate that the impact of such storms is increasingly significant in populated urban areas due to changing environmental conditions.

Recently, a significant hail event struck the Tangerang region in Banten on October 31, 2025. This event mirrors similar convective occurrences in Java, where rapid cloud growth and temperature drops are key precursors. Based on community reports and radar observations, the hail event was highly localized, specifically impacting the Gading Serpong area (Kelapa Dua District) and extending to the Jelupang area (North Serpong District). Reports indicated hail accompanied by strong winds causing significant impacts in these densely populated zones (Tristiawati, 2025). This incident is particularly notable as it occurred in a developed urban area, where the Urban Heat Island (UHI) effect can locally enhance convective initiation and storm intensity.

Operational mitigation of hail relies heavily on early detection and atmospheric profiling. Doppler Weather Radar is the primary tool for detecting high-reflectivity cores associated with hail. Furthermore, satellite imagery from Himawari-8/9 allows for the detection of overshooting tops and cloud top cooling, which are signatures of severe updrafts penetrating the tropopause (Bessho et al., 2016). However, remote sensing alone cannot fully resolve the thermodynamic environment, such as the vertical distribution of temperature and humidity, which determines the potential for ice growth and melting.

To characterize the vertical atmospheric profile, radiosonde observations are widely considered the gold standard for in-situ upper-air measurements. However, the spatial and temporal scarcity of radiosonde launches limits their utility for capturing localized storms. Consequently, numerical weather prediction (NWP) models, such as the ERA5 reanalysis and forecasts from the European Centre for Medium-Range Weather Forecasts (ECMWF), are essential for filling these observational gaps (Hersbach et al., 2020). Nevertheless, discrepancies between global models and tropical observations persist. Previous studies, such as Mulsandi et al. (2021), highlight that reanalysis data often exhibit moisture biases and may smooth out extreme instability gradients in the tropics, necessitating rigorous validation against local soundings.

Therefore, this study aims to identify the vertical atmospheric conditions associated with the hail event in Tangerang on 31 October 2025 through a comparative analysis. While previous studies have focused on general radar characteristics or climatology, there is a lack of quantitative evaluation regarding how well the ECMWF model represents the specific hail-favoring profiles, specifically freezing level and CAPE, in an Indonesian urban setting. This study compares ECMWF profiles with radiosonde observations and validates them against radar data to determine the model's reliability and understanding of the storm's thermodynamic drivers.

2. MATERIALS AND METHODS

2.1. Materials

The main datasets used in this study consist of remote sensing data and atmospheric observation data. Himawari-9 satellite infrared imagery (Channel 13) and C-band weather radar data were obtained from the

Meteorology Directorate of the Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG). Upper-air observation data were derived from radiosonde soundings obtained from the University of Wyoming database, corresponding to station ID 96749 (Soekarno–Hatta Meteorological Station), located at 6.24°S and 106.63°E. Radiosonde observations at 00 and 12 UTC were used.

Global model data were obtained from the ERA5 reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts, accessed through the Climate Data Store platform. ERA5 pressure-level data with a horizontal resolution of 0.25° × 0.25° (~30 km) were extracted at grid points nearest to the radiosonde station location for 00 and 12 UTC on 31 October 2025.

Convective instability was assessed using mixed-layer Convective Available Potential Energy (MLCAPE), defined as the parcel averaged over the lowest 50 hPa of the atmosphere. Radiosonde profiles were vertically interpolated to standard pressure levels to match ERA5 data using linear interpolation. Model performance was quantitatively evaluated using bias and root mean square error between ERA5 and radiosonde-derived parameters, including freezing level height, lapse rate, and MLCAPE.

2.2. Methods

This study uses a case study approach by integrating remote sensing data and numerical models. Data processing is performed computationally using Python programming scripts on the Google Colab platform. Specifically, the MetPy library was utilized to extract and visualize atmospheric parameters such as pressure, temperature, dew point, and wind profiles (May et al., 2022). These parameters are then analyzed to calculate the atmospheric stability index and generate vertical profiles (Skew-T Log-P diagrams). The level of atmospheric instability was analyzed based on the Convective Available Potential Energy (CAPE) value, which refers to the classification standard established by the National Weather Service (n.d.), as shown in Table 1. In addition, the storm cell structure was validated using the Column Maximum (CMAX) and Vertical Cut (VCUT) products from radar data processed using Rainbow® 5 software (Leonardo Germany GmbH, 2018). The analysis method focused on a comparative test between the ECMWF model thermodynamic profile and in-situ observation data (radiosonde) to evaluate the accuracy of the model in representing atmospheric instability conditions (**Table 1**).

Table 1. CAPE Classification (Data Source: National Weather Service)

CAPE (J/kg)	Instability Level
< 1000	Weak Instability
1000 – 2500	Moderate Instability
2500 – 4000	Strong Instability
> 4000	Extreme Instability

3. RESULTS AND DISCUSSION

This section presents the results of an analysis of meteorological conditions and the vertical structure of the atmosphere during the hailstorm in Tangerang on October 31, 2025.

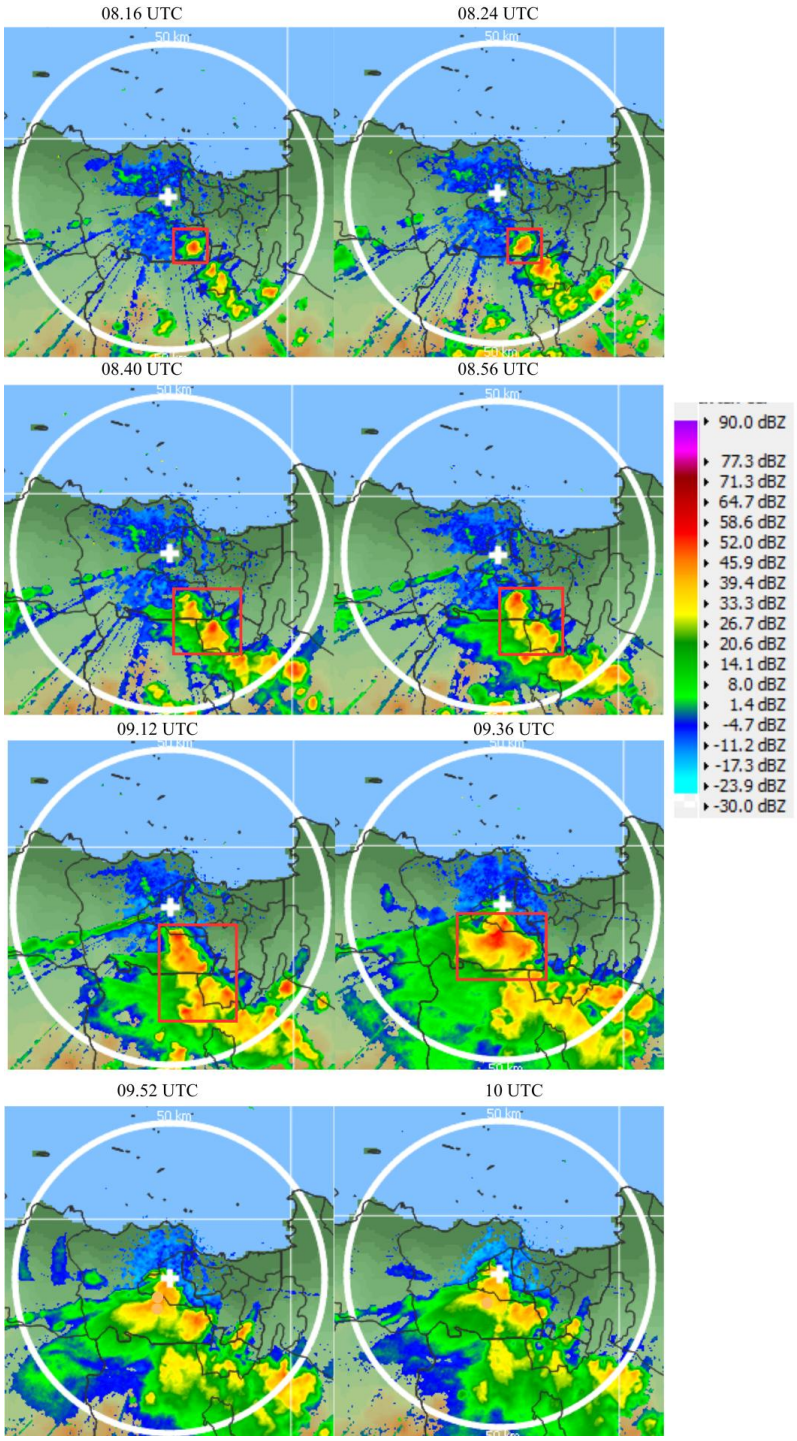

Figure 1. Tangerang Radar CMAX Product

The discussion covers the spatial and temporal evolution of convective clouds based on radar and satellite imagery, as well as a comparison of thermodynamic profiles between observational data and numerical models to understand the instability mechanisms that occurred. Analysis of storm cell evolution based on C-Band radar reflectivity (**Figure 1**) shows a maximum value exceeding 50 dBZ in the storm core moving from Depok to Tangerang. Physically, this high reflectivity value indicates the presence of large solid hydrometeors (ice grains) that trigger strong radar wave backscattering (Mie scattering). This is in line with the findings of Ardiansyah (2022) in the Meteorology, Climatology, and Geophysics Bulletin, which states that radar reflectivity values of up to 60 dBZ are a strong indicator of the mature phase of clouds causing hail. This indication of explosive cloud growth is reinforced by data from the Himawari-9 satellite, which detected a Cloud Top Temperature reaching -80°C. This extreme cooling indicates an overshooting top that penetrates the tropopause, as explained by Nugraha and Fadlan (2018), who found that cloud top temperatures below -77°C have a significant correlation with hail occurrences in tropical regions.

From a thermodynamic perspective, although the CAPE value is moderate, this event is significantly influenced by the freezing level altitude. According to Fadholi (2013) in the Indonesian Journal of Physical Sciences, even though Indonesia has a relatively higher freezing level compared to mid-latitudes, hail can still reach the surface if supported by strong downdrafts and high humidity, which prevent the ice grains from melting completely. Finally, validation of global model data against in-situ observations shows that the model tends to underestimate the peak instability index. This bias is consistent with the study by Mulsandi et al. (2021) who evaluated model performance in Indonesia, where model/reanalysis data often has limitations in capturing extreme values of local-scale convective parameters, but still represents atmospheric spatial and temporal patterns quite well.

Figure 2 shows the results of VCUT Radar, which displays the vertical conditions of the atmosphere. The time selected is when hail occurred in the Tangerang area, which was at 09:36 UTC or 16:36 WIB. At an altitude of between 2 and 4 km, which is the freezing level, there was high reflectivity of >50 dBZ. This indicates the presence of ice crystals formed at that altitude.

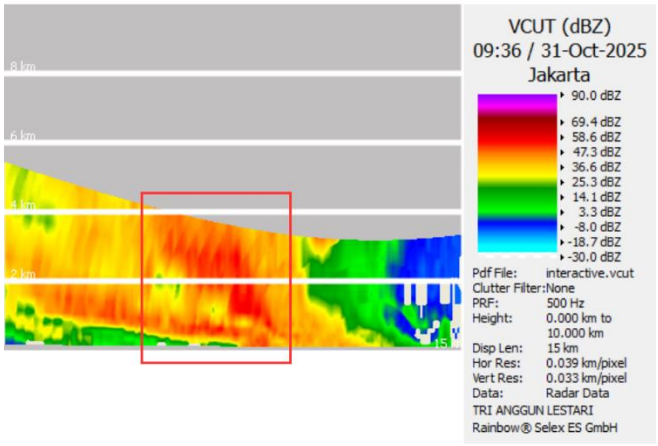

Figure 2. Tangerang Radar VCUT Product

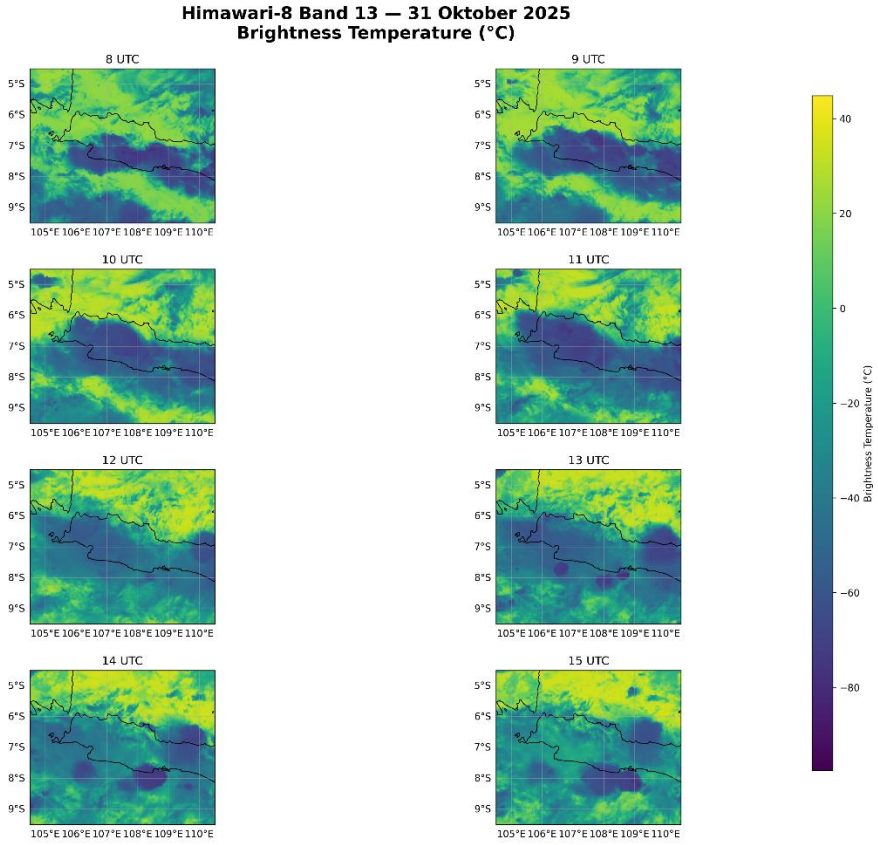

Figure 3. Peak Cloud Temperature Development Throught Satellite Images

Figure 3. illustrates the spatial distribution of the minimum brightness temperature observed during the hailstorm in Tangerang. At 08:00 UTC, convective clouds with extremely cold cloud tops were observed stretching from the southern to the central region of West Java. From 09:00 UTC to 13:00 UTC, the system intensified and expanded, covering the entire West Java region, including Tangerang.

The cloud top temperature reached approximately -60 °C. This significant temperature drop indicates a rapid vertical development penetrating the tropopause layer. Such extreme cooling corresponds to the Overshooting Top (OT) signature, which is statistically strongly correlated with severe weather events, including hail and damaging winds (Bedka et al., 2010).

Evaluation of the atmospheric vertical profiles at 00 UTC (**Figure 4**) and 12 UTC (**Figure 5**) provides crucial insights into the performance of the ECMWF model and the physical mechanisms of hail formation. At 00 UTC, data comparison shows that although the model is able to represent the lower-layer moisture structure well, it tends to underestimate the intensity of thermodynamic instability (CAPE) compared to in-situ observations.

This bias is a consequence of the global model resolution that averages local-scale convective parameters, where reanalysis data in the tropics often suffers from a wet bias but fails to capture the sharp temperature lapse rate, as explained in the model evaluation by Mulsandi et al. (2021). Despite the quantitative discrepancy reflected in the RMSE values, the qualitative agreement of the

vertical profile patterns confirms that the model remains valid for identifying pre-convective environments, as the bias does not eliminate the key physical signal of massive water vapor availability. Furthermore, analysis at 12 UTC during the mature phase of the storm revealed that this hail event formed under moderate CAPE conditions, in contrast to the characteristics of subtropical storms which are generally triggered by extreme instability energy.

The success of hail formation under these moderate energy conditions was predominantly controlled by the observed freezing level height at 4.8 km. Referring to the findings of Fadholi (2013), a freezing level height in the range of 4–5 km is an ideal condition in the Indonesian region that allows ice grains to have sufficient residence time in the cold layer to grow, as well as a short enough fall distance to reach the ground surface without melting completely, supported by a thick moisture profile (deep moisture) that protects the updraft column from dry air entrainment.

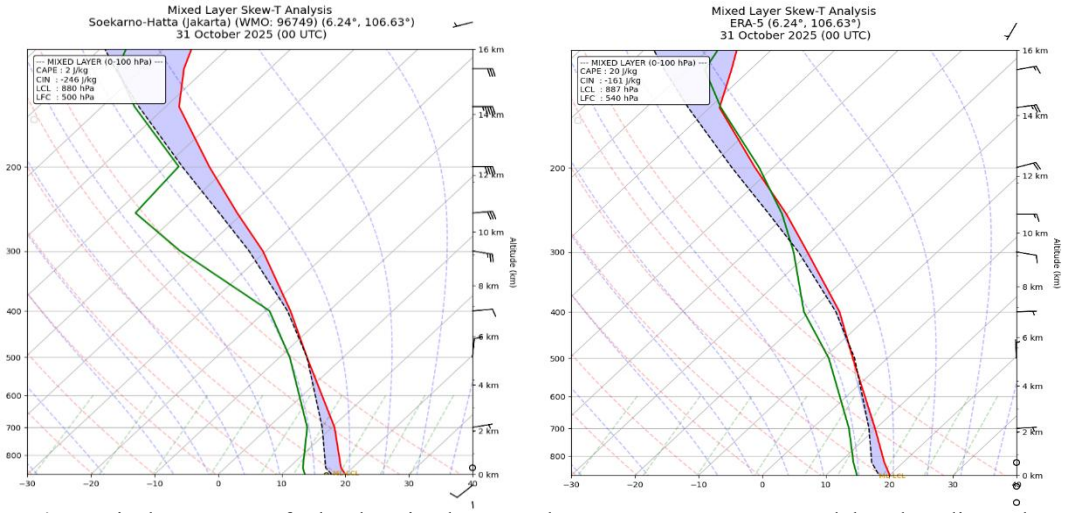

Figure 4. Vertical Structure of Clouds Mixed Layer Skew-T Data ECMWF Model and Radiosonde Data 00 UTC

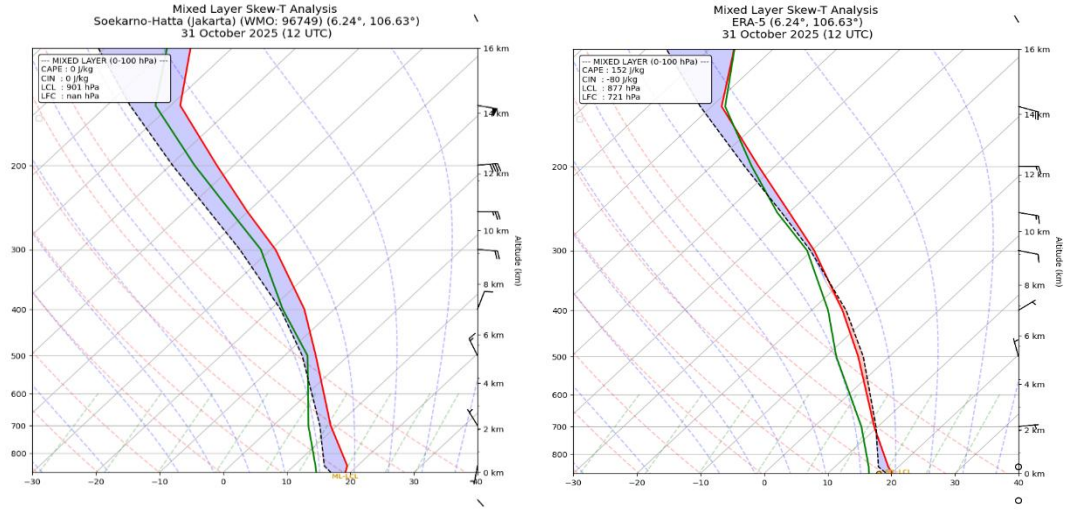

Figure 5. Vertical Structure of Clouds Skew-T Log-P Data ECMWF Model and Radiosonde Data 12 UTC

Table 1. Bias and RMSE Values of Temperature and Dewpoint Parameters between Model and Radiosonde Data at 00 UTC and 12 UTC

Time	Temperature Bias	RMSE Temperature	Bias Dewpoint	RMSE Dewpoint
00 UTC	0,277401924	0,952667642	3,603164291	6,375474701
12 UTC	0,565832825	1,591942278	1,666738281	2,398636698

A comparative analysis of the atmospheric profiles in **Figures 4.** (00 UTC) and **Figure 5.** (12 UTC) shows characteristic differences between the ECMWF model predictions and radiosonde observational data. At 00 UTC, the model predicts a higher convective energy (CAPE) value than the observational data. The primary cause of this discrepancy is confirmed through statistical evaluation in **Table 1.** which shows a dewpoint bias of +3.60°C. This positive bias indicates that the model estimates atmospheric conditions that are much more humid than actual conditions, directly causing an overestimation of potential storm energy. This phenomenon of overestimated humidity in the model in tropical regions is consistent with the findings of Mulsandi et al. (2021). In addition to model bias, differences in data collection locations between Soekarno-Hatta Airport (for observations) and the event point in South Tangerang (for the model) also contribute to this variation, given the highly localized nature of convective clouds.

Furthermore, at 12 UTC during the mature phase of the storm, the decrease in humidity bias to +1.67°C in **Table 1.** is followed by observational data indicating that hail formed under conditions of moderate, rather than extreme, instability. This proves that hail formation in the study area does not solely depend on the magnitude of CAPE energy. Referring to Fadholi (2013), the determining factor for hail success in this case is the freezing level altitude, which is at 4.8 km. This altitude is ideal because it provides sufficient time for ice grains to grow, but the fall distance is short enough to prevent complete melting before reaching the surface. Thus, despite differences in quantitative values due to humidity bias and location, both datasets qualitatively successfully identify the saturated atmospheric structure that supports storm cloud growth.

4. CONCLUSION

The analysis of the hail event in Tangerang reveals that deep convection in tropical environments can produce severe weather even under conditions of limited thermodynamic instability. Remote sensing analysis confirmed the severity of the storm cell, where C-Band Weather Radar detected reflectivity values exceeding 50 dBZ and Himawari-9 satellite imagery observed Cloud Top Temperatures reaching -80°C, signifying large hydrometeors and vigorous updraft penetration. Thermodynamically, the event was driven not by extreme instability—as indicated by negligible Radiosonde CAPE (0–2 J/kg) and weak ECMWF model instability (20–152 J/kg)—but rather by a favorable freezing level at 4.8 km and deep moisture availability that sustained the ice phase despite significant convective inhibition. A comparative evaluation highlights a distinct "wet bias" in the ECMWF model, characterized by a positive dewpoint bias of +3.60°C at 00 UTC, which led to an overestimation of instability compared to in-situ soundings: a discrepancy attributed to global model limitations in resolving local humidity and spatial differences between grid points. Consequently, operational forecasting in Indonesia should not rely solely on high CAPE thresholds but must integrate radar signatures with freezing level monitoring,

while future research should address the limitations of coarse global models by utilizing high-resolution mesoscale models (e.g., WRF) to better resolve the explicit microphysical processes of tropical hail.

ACKNOWLEDGMENT

The author would like to express his sincere gratitude to the University of Wyoming and the European Centre for Medium-Range Weather Forecasts (ECMWF) for providing access to radiosonde data and ERA5 reanalysis data that were essential for the completion of this study. The author also thanks the Sekolah Tinggi Meteorologi, Klimatologi, dan Geofisika (STMKG) as the institution where the author studied, for providing the facilities and a conducive academic environment that enabled this research to be completed successfully.

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