

# MICROPHYSICAL AND DYNAMICAL CHARACTERISTICS OF HAIL-BEARING CONVECTIVE CLOUDS IN DEPOK: THE CASE OF 28 OCTOBER 2024

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## Abstract

*This study investigates the microphysical and dynamical characteristics of hail-producing convective clouds over the Depok region, Indonesia, through a case study of the event on 28 October 2024. A multi-data approach was applied by integrating weather radar data, Himawari-9 satellite, and ERA5 atmospheric reanalysis. Radar analysis revealed intense convective cores with reflectivity exceeding 55–60 dBZ, high Vertically Integrated Liquid (VIL) values (~50 mm), and ZHAIL probabilities above 80%, indicating well-developed hail cores. Satellite observations showed cloud growth and extremely low cloud-top temperatures coinciding with peak radar signatures. Although Convective Available Potential Energy (CAPE) values were relatively modest, reanalysis data indicated strong moisture availability, deep-layer instability, and favorable wind shear. These results demonstrate that hail formation in tropical urban regions is driven by the combined effects of moisture-rich environments, deep atmospheric instability, and [1,2]organized convective dynamics rather than by high CAPE alone.*

**Keywords:** *Hail; Weather radar; Atmospheric instability; ERA5 reanalysis.*

## INTRODUCTION

Indonesia's tropical maritime environment is characterized by high solar insolation and abundant low-level moisture, fostering an atmosphere primed for intense convective development [1,2]. Within this framework, deep convective systems often evolve into Cumulonimbus clouds, which are frequently responsible for extreme weather phenomena, including thunderstorms and hail, through the rapid release of latent heat [3,4]. In the Indonesian archipelago, these processes are further modulated by complex interactions between surface heating and mesoscale circulations [5].

Hail formation, in particular, represents a sophisticated interplay of cloud dynamics and microphysics [6]. It necessitates sustained, powerful updrafts capable of lofting ice embryos above the 0°C isotherm, where they grow through riming and accretion in the presence of supercooled liquid water [7]. The eventual diameter and impact of hailstones at the surface are dictated by the equilibrium between updraft velocity and gravitational forces [8]. Given the deep vertical structure of tropical convection, a comprehensive

assessment of the atmospheric column is vital to identifying the specific parameters that drive hail intensification.

The utilization of ERA5 reanalysis data offers a robust framework for overcoming the spatial gaps inherent in sparse observation networks. In this study, we analyze variables such as CAPE, moisture flux convergence, and vertical wind profiles from ERA5 to isolate the environmental conditions conducive to severe mesoscale convection [9–11]. Data assimilation system within ERA5 ensures a consistent physical representation of the atmospheric state, even in regions with limited surface coverage [12].

Complementing reanalysis data, weather radar serves as the primary tool for monitoring the real-time internal architecture of storm cells. Radar reflectivity allows for the precise mapping of hydrometeor distribution, distinguishing between liquid precipitation and ice cores [13,14]. Advanced products such as Vertically Integrated Liquid (VIL) and hail detection algorithms (ZHAIL) have become indispensable for identifying high-reflectivity cores aloft that indicate imminent hailfall

[15,16]. The integration of Constant Altitude Maximum Reflectivity (C<sub>MAX</sub>) and Vertical Cut (VCUT) provides a three-dimensional diagnostic of cloud intensity, which is critical for verifying the presence of large ice particles [17,18].

This study investigates the technical dynamics of a significant hail event that occurred in Depok City on 28 October 2024. Between 13:00 and 16:00 WIB, intense convective cells triggered very heavy rainfall and hail, causing localized damage to urban infrastructure. This research aims to characterize the atmospheric instability and microphysical structure responsible for this event by synthesizing ERA5 reanalysis data with Tangerang Radar observations. By focusing on stability parameters and radar-derived hail indicators, this paper seeks to provide a definitive technical account of the mechanisms that allowed hailstones to reach the surface in a tropical urban environment, serving as a reference for future early warning localized forecasting.

## METHODOLOGY

### Research Location

This study focuses on the administrative regions of Depok City in West Java Province, Indonesia, based on Figure 1. Geographically, the study area is located within the latitude range of 6.30° S to 6.70° S and the longitude range of 106.70° E to 106.95° E.

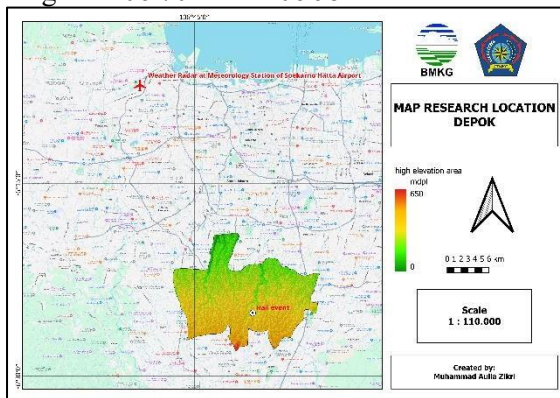


Figure 1. Research location map showing Depok City and the coverage area of the Tangerang C-band Doppler Weather Radar

### Research Procedure

#### Weather Radar Data Processing

Weather radar data were processed using the Rainbow DART software (Selex ES),

which is widely used for operational Doppler radar data processing. The data were obtained from a C-band Doppler weather radar located in Tangerang, with a temporal resolution of 10 minutes per volume scan. Raw radar data in HDF5 format containing reflectivity (Z), radial velocity (V), and spectrum width (W) were first extracted and subsequently processed through a preprocessing stage that included corrections for ground clutter and signal attenuation effects. The corrected data were then converted into (.vol) format as radar volume data, which were used to generate various derived products such as MAX, C<sub>MAX</sub>, Vertically Integrated Liquid (VIL), and Hail Detection Algorithm (ZHAIL). The ZHAIL product estimates the probability of hail at the surface by identifying reflectivity cores above the freezing level and assessing their downward extent. These configurations included the application of high reflectivity thresholds to detect ice particles and intense convective systems. Radar products were generated by rendering the radar volume data using predefined configuration parameters, including a reflectivity threshold of 45 dBZ for ice particle detection.

#### Satellite Data Processing

Satellite data files in NetCDF (.nc) format were downloaded via the File Transfer Protocol (FTP) using FileZilla software with restricted access, directly connected to an internal data distribution server, ensuring the availability of high-resolution Himawari-9 satellite data. The NetCDF data were then imported into the SATAID software to extract Cloud Top Temperature (CTT) values. This software enables interactive identification of convective cloud structures, including the determination of coordinates corresponding to the coldest cloud tops, which serve as proxies for identifying overshooting tops during the peak convective phase.

#### ECMWF Reanalysis Data Processing

ERA5 reanalysis data processing was performed programmatically using the Python programming language within the Google Colab environment. Analyses were performed using data across multiple pressure levels, ranging from 1000 hPa to 100 hPa, to capture the full vertical extent of the troposphere. The processing steps included:

- a. Retrieving data from the Climate Data Store (C3S) using the cdsapi library for the event's coordinates and time period.
- b. Processing NetCDF data using the xarray library for variable extraction and MetPy for thermodynamic parameter calculations (e.g., CAPE, Lifted Index (LI), Showalter Index (SI), etc.), specifically to generate time series of Convective Available Potential Energy (CAPE) and other stability indices.
- c. Developing Python scripts to generate Hovmöller diagrams of relative humidity (RH) and vertical velocity ( $w$ ) profiles to analyze hourly vertical atmospheric dynamics at the event location.

### Data Analysis

The analysis focused on integrating multi-source spatial data to characterize the hail event. Radar data processing involved preprocessing steps such as clutter removal and attenuation correction, followed by volume rendering to generate radar-derived products for identifying intense reflectivity cores and hail probability using a reflectivity threshold of 45 dBZ. The analysis utilized CMAX and VCUT products to diagnose the vertical development of the storm. Satellite data were processed to identify the temporal evolution of cloud top cooling.

ERA5 reanalysis data were processed programmatically to provide the environmental context. Thermodynamic calculations were conducted to evaluate the atmospheric instability evolution, focusing on CAPE and vertical wind profiles. Vertical profiles and Hovmöller diagrams of relative humidity and vertical velocity were generated to analyze atmospheric dynamics during the hail event. All analysis techniques were aligned with the research objectives to comprehensively assess the microphysical and dynamical characteristics of the hail-producing convective cloud system without the reliance on point-based surface observations.

## RESULT

### Weather Radar Analysis

#### a. CMAX Product

Analysis of the CMAX product, as shown in Figure 2 during the event, revealed the development of highly intense convective cells over Depok City on 28 October 2024.

The peak mature phase was observed between 15:18 and 15:42 WIB, during which maximum reflectivity values reached approximately 55–60 dBZ, represented by deep red to purple colors on the radar imagery. Meteorologically, reflectivity values exceeding the 55 dBZ threshold in tropical regions are a strong indicator of the presence of hail cores or high concentrations of ice particles within Cumulonimbus clouds. The presence of these storm cores with extreme reflectivity provides a physical justification for reported surface observations of very heavy rainfall accompanied by hail and strong winds in the affected areas. The use of the CMAX product proved effective in identifying maximum storm intensity throughout the vertical atmospheric column up to an altitude of 10 km.

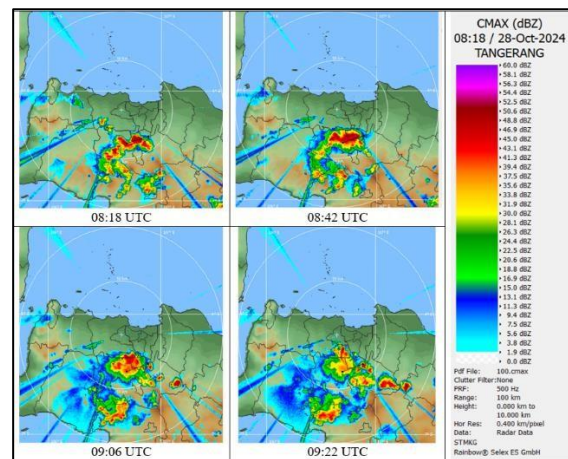


Figure 2. CMAX Product

As the system progressed toward 16:06 WIB, the spatial extent of high-intensity rainfall was observed to expand significantly, particularly toward the southern regions. Although areas of strong intensity persisted, the purple color signatures ( $\approx 60$  dBZ) began to diminish during this period, indicating that the system was starting to pass its peak energy phase. By 16:22 WIB, the system had clearly entered the dissipation stage, characterized by a pronounced reduction in red-colored areas on the radar imagery. This decrease in reflectivity values reflects the weakening of the convective system after the release of latent energy in the form of heavy precipitation over the Depok region.

#### b. VIL Product

Analysis of the Vertically Integrated Liquid (VIL) product, as shown in Figure 3,

was conducted to estimate the total amount of liquid water and ice particles accumulated within a vertical atmospheric column. Based on radar imagery during the peak period of the event between 15:18 and 15:42 UTC, a highly significant concentration of VIL values was observed, reaching up to 50.1 mm (red shading) over Depok City. Physically, such elevated VIL values indicate a substantial accumulation of hydrometeor mass within the convective cloud, sustained by very strong updrafts. The observed surge in VIL values during this period suggests the occurrence of heavy rainfall and hail at the surface, as the water mass retained in the upper layers of the cloud is released almost simultaneously when the updraft begins to weaken.

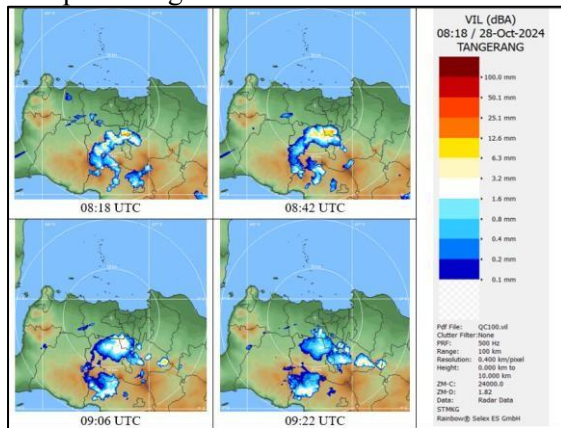


Figure 3. VIL Product

As the system entered the dissipation phase, VIL values were observed to decrease drastically as precipitation descended to the surface. At 16:22 UTC, the estimated water content within the atmospheric column diminished to approximately 1.6 mm, as indicated by the transition to light blue shading on the radar imagery. This reduction confirms that the potential energy within the convective system had been fully released, leading to a gradual weakening of rainfall intensity over the affected regions. Technically, the VIL product configuration was set for a vertical range of 0–10 km with a spatial resolution of 0.4 km per pixel and a radar range of up to 100 km, providing high-precision detail for monitoring the storm life cycle from the mature stage through dissipation.

*c. ZHAIL Product*

The ZHAIL analysis in Figure 4 provides information on the potential occurrence of hail over the Depok regions

during the peak convective phase. During the period from 15:18 to 15:42 UTC, radar imagery indicated areas with hail occurrence probabilities exceeding 80% (brown to dark red shading). These very high probability values show a strong positive correlation with reflectivity values greater than 55 dBZ and the previously observed surge in VIL values, indicating that the internal cloud structure contained a well-developed hail core. Technically, this algorithm operates using a minimum reflectivity threshold of 45 dBZ and incorporates the freezing level height at approximately 3.0 km to estimate the presence of ice particles descending to altitudes as low as 1.4 km above the surface. The emergence of these maximum probability signals serves as key scientific evidence supporting field reports of hailfall events.

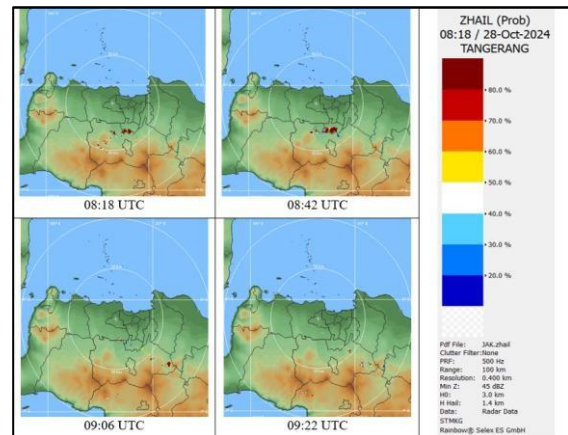


Figure 4. ZHAIL Product

As the updraft weakened, the probability of hail occurrence was observed to decrease sharply in the subsequent hours. Between 16:06 and 16:22 WIB, the radar imagery became dominated by blue shading, indicating that the probability of hail occurrence had dropped below 20%. This marked decline suggests that most ice particles within the cloud either precipitated as heavy rainfall or melted before reaching the surface due to the loss of mechanical support from vertical air motions. Time-series observations of the ZHAIL product proved highly effective in precisely constraining the temporal window of the extreme event within a 100 km radius from the radar center.

**Weather Satellite Analysis**

Based on Himawari-9 satellite imagery from the Enhanced Infrared (EH) channel in

Figure 5 dated 28 October 2024, a very significant development of convective clouds was observed over western Java, particularly in the Depok region. At 15:00 WIB, a rapid cloud growth phase was evident, which subsequently reached its peak at approximately 15:30 WIB. This phase was characterized by the emergence of deep red to pink shading at the core of the storm cells, indicating extremely low Cloud Top Temperature (CTT) values. This pronounced decrease in cloud-top temperature represents the presence of very strong updrafts penetrating toward, and possibly above, the tropopause layer, which is a key characteristic of hail-producing Cumulonimbus clouds.

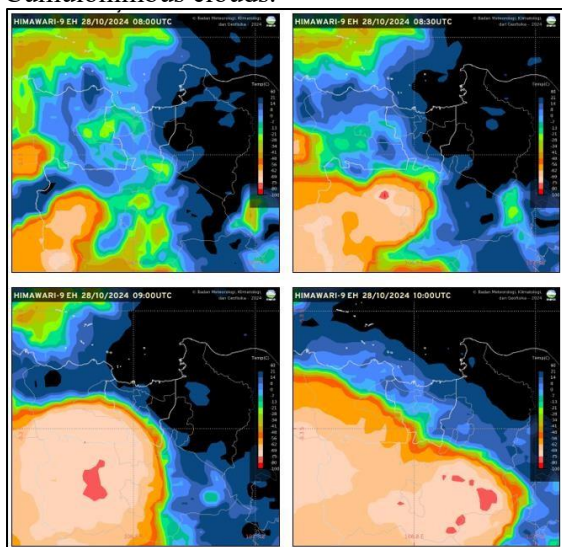


Figure 5. Himawari Satellite

By 16:00 UTC, cloud coverage was observed to expand spatially, while the convective core with the coldest cloud-top temperatures remained persistent, indicating that intense storm activity was still ongoing. By 17:00 UTC, the cloud structure began to exhibit signs of dissipation, as the red-colored core areas spread and thinned, gradually being replaced by a broader anvil cloud shield (orange/yellow shading). The cloud-top temperature dynamics captured by the satellite imagery show a strong temporal correlation with radar observations, in which the overshooting top phase at approximately 15:30 WIB coincided with the detection of maximum reflectivity and the occurrence of hail at the surface.

## ECMWF – ERA 5 Analysis

### a. Air Stability Index – CAPE

Based on the analysis of atmospheric stability indices shown in Figure 6, the CAPE profile over the Depok region exhibits a diurnal fluctuation pattern, reaching its peak concurrently with the extreme weather event. During the hail occurrence period (15:18 – 15:42 WIB), CAPE values increased and reached a daily maximum of approximately  $600 \text{ J kg}^{-1}$ . According to general classification, this value remains below the threshold for moderate instability ( $1000 \text{ J kg}^{-1}$ ) and is therefore categorized as weak instability. However, the presence of positive potential energy indicates that the atmosphere during the afternoon hours still possessed sufficient buoyancy to lift moist air parcels and support the development of convective clouds.

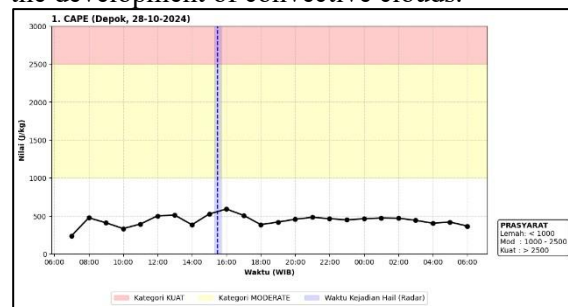


Figure 6. Time series of CAPE over Depok on 28 October 2024. The shaded area indicates the hail event period.

Although the absolute CAPE values derived from ERA5 reanalysis appear relatively low, the temporal trend shows a strong relationship between the availability of maximum energy and the timing of the hail event. The CAPE peak occurring at approximately 16:00 WIB confirms that the release of atmospheric instability energy took place nearly simultaneously with the detection of maximum radar reflectivity. The relatively small magnitude of CAPE is likely influenced by the spatial resolution of the ERA5 model, which averages atmospheric conditions over a relatively large grid area ( $0.25^\circ$ ), thereby smoothing extreme values at the microscale. Nevertheless, the presence of positive CAPE values satisfies a fundamental requirement for validating the potential development of Cumulonimbus clouds at the study location.

*b. Air Stability Index – SWEAT*

Analysis of the SWEAT index in Figure 7 reveals a consistent increasing trend in severe weather potential toward the afternoon over the Depok region. Throughout the observation period from morning to midday, the index curve exhibits a steady rise and remains within the moderate category (yellow shading). During the hail occurrence period (15:18 – 15:42 WIB), SWEAT values reached their peak, ranging between approximately 220 and 225. These values closely approach the upper threshold of the moderate category (239), providing strong evidence that the atmosphere possessed a sufficient combination of thermal instability and wind shear to trigger hail-producing convective phenomena.

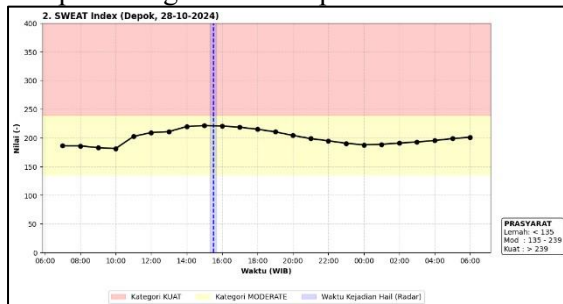


Figure 7. Time series of SWEAT over Depok on 28 October 2024. The shaded area indicates the hail event period.

The elevated SWEAT values observed during the event represent strong atmospheric dynamic support, particularly the interaction between low-level moisture and vertical variations in wind direction and speed. The close temporal correspondence between the SWEAT peak and the timing of the hail event confirms that the atmospheric environment was highly conducive to the development of convective systems capable of sustaining strong updrafts. Although the index values did not exceed the “severe” category threshold (>239), SWEAT values exceeding 200 in tropical regions are already considered a valid indicator of the potential for severe thunderstorm activity, including hail-producing storms.

*c. Air Stability Index – K Index*

Analysis of the K-Index (KI) profile shown in Figure 8 indicates a significant increase in mid-level atmospheric moisture availability over the Depok region throughout the event day. Since the morning hours, the KI

curve exhibits a consistent upward trend and enters the moderate instability category (yellow shading) beginning at approximately 11:00 WIB. During the hail occurrence window (15:18–15:42 WIB), KI values were observed to range between approximately 34 and 35 °C. Meteorologically, KI values exceeding 30 °C indicate a high convective potential with a strong probability of thunderstorm development, supported by abundant moisture in the 850–700 hPa layer.

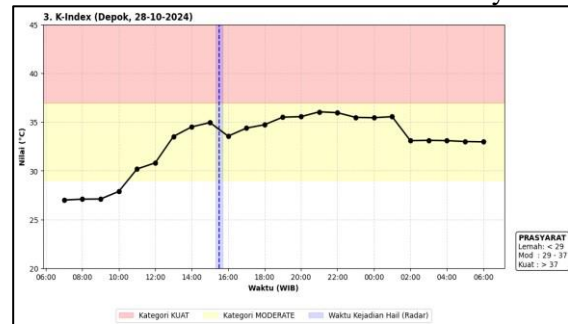


Figure 8. Time series of K Index over Depok on 28 October 2024. The shaded area indicates the hail event period.

The elevated KI values observed during the event serve as a key indicator that the atmosphere at that time contained sufficient moisture to support the development of thick and deep Cumulonimbus clouds. Such conditions minimize the suppressing effects of dry air entrainment, which typically inhibits vertical cloud growth. Although the KI time series indicates that the maximum values were reached later in the evening, the values recorded during the afternoon had already exceeded the critical threshold for air-mass thunderstorm formation. This high moisture availability, when combined with lifting mechanisms associated with atmospheric instability (CAPE) and wind shear (SWEAT), created an ideal environment for the formation of ice particles within the cloud before their descent to the surface.

*d. Air Stability Index – Total Totals Index*

The Total Totals Index (TT) profile shown in Figure 9 exhibits a consistent upward trend in accumulated atmospheric energy from morning to afternoon over the Depok region. During the hail occurrence window (15:18–15:42 WIB), TT values were observed to range between approximately 44.6 and 45.0 °C. These values fall within the moderate instability category (yellow shading) and

approach the threshold for strong instability ( $>46\text{ }^{\circ}\text{C}$ ). Physically, these elevated TT values represent a combination of a steep vertical temperature gradient (lapse rate) between the 850 hPa and 500 hPa layers and high moisture content in the lower troposphere. Such conditions create an atmospheric environment highly favorable for the development of intense thunderstorm-producing clouds.

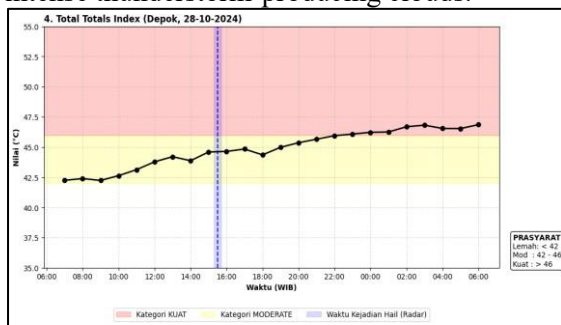


Figure 9. Time series of TT Index over Depok on 28 October 2024. The shaded area indicates the hail event period.

The correlation between the increasing TT values and the timing of the event is clearly evident, as the profile shows a sustained positive trend leading up to the occurrence. TT values around  $45\text{ }^{\circ}\text{C}$  during the afternoon indicate that the atmosphere featured an extreme combination of warm, moist air in the lower layers and cold, dry air aloft. This strong thermal contrast serves as a primary energy source for explosive Cumulonimbus cloud development. The elevated TT values observed during the event provide additional validation that the vertical atmospheric structure at that time was highly unstable, allowing air parcels to continue rising and sustaining strong updrafts up to the freezing level, where ice particle formation occurs.

#### e. Air Stability Index – Lifted Index

Based on the Lifted Index (LI) profile shown in Figure 10, the atmosphere over the Depok region had already exhibited unstable conditions since the morning, as indicated by consistently negative values. During the peak of the hail event (15:18–15:42 WIB), LI values were observed to range between approximately  $-3.8$  and  $-4.0\text{ }^{\circ}\text{C}$ . These values fall within the moderate instability category, which is theoretically sufficient to support deep convection and thunderstorm development. Although the lowest (most unstable) LI value reached approximately  $-6\text{ }^{\circ}\text{C}$  during the

morning hours (around 09:00 WIB), the persistence of negative LI values into the afternoon indicates that atmospheric buoyancy remained sustained throughout the day, awaiting an afternoon trigger to release the accumulated energy.

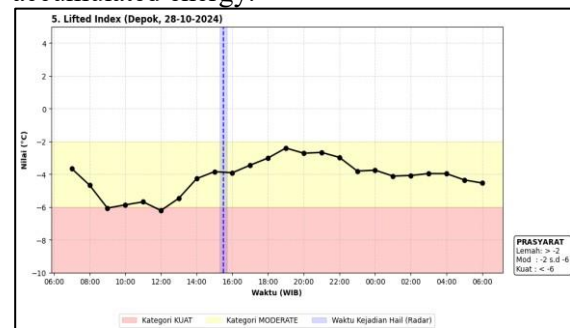


Figure 10. Time series of Lifted Index over Depok on 28 October 2024. The shaded area indicates the hail event period.

The presence of negative LI values during the event confirms that air parcels lifted adiabatically from the surface remained warmer than the surrounding environment at the 500 hPa level. A temperature difference of approximately  $4\text{ }^{\circ}\text{C}$  provides significant positive buoyancy, allowing clouds to grow vertically and penetrate toward the tropopause layer. In the context of hail events, LI values around  $-4$  are highly relevant indicators, as they suggest that the resulting updrafts possessed sufficient vertical velocity to suspend ice particles, preventing their premature descent while allowing further growth through accretion processes within the cloud.

#### f. Air Stability Index – Showalter Index

Analysis of the Showalter Index (SI) shown in Figure 11 provides a specific depiction of atmospheric instability above the surface by lifting an air parcel from the 850 hPa level. The profile indicates that SI reached its minimum (most unstable) value precisely during the event. Between 15:00 and 16:00 WIB, SI decreased to approximately  $-3.0\text{ }^{\circ}\text{C}$ , representing the lowest value throughout the 24-hour observation period. The close temporal alignment between the peak SI instability and the timing of radar detections provides strong evidence that instability within the 850 hPa layer played a key role in the initiation of the afternoon storm.

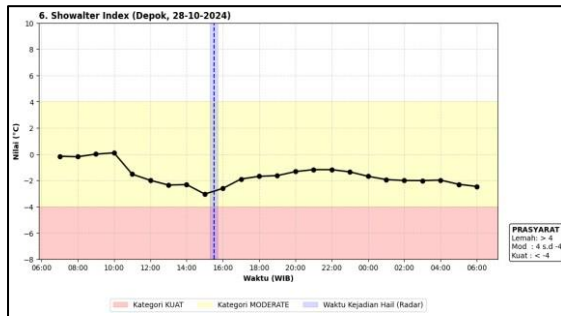


Figure 11. Time series of SI over Depok on 28 October 2024. The shaded area indicates the hail event period.

An SI value of  $-3.0\text{ }^{\circ}\text{C}$  falls within the moderate-to-strong instability category, which is commonly associated with the potential for severe thunderstorm development. Unlike the Lifted Index (LI), which is based on surface parcels, the negative SI values confirm that the mid-level atmosphere (850–500 hPa) was also highly unstable and moisture-rich. This condition is particularly critical for hail events, as it indicates that even if the surface layer is influenced by local factors, the overlying layers remain highly supportive of vigorous cloud growth. The combination of negative SI values and elevated TT further reinforces the conclusion that the storm system was not merely a result of isolated thermal convection, but rather an organized system supported by deep-layer atmospheric instability.

## CONCLUSIONS

This study confirms that the hail event over Depok City on 28 October 2024 was generated by a well-organized convective system supported by favorable thermodynamic, dynamic, and microphysical conditions. The integration of surface observations, weather radar, Himawari-9 satellite data, and ERA5 reanalysis proved effective in capturing the multiscale atmospheric processes responsible for hail formation in a tropical urban environment.

Weather radar analysis revealed intense convective cores characterized by maximum reflectivity values exceeding 55–60 dBZ, elevated VIL values reaching approximately 50 mm, and ZHAIL probabilities greater than 80% during the mature phase of the storm. These signatures provide strong physical evidence of well-developed hail cores within Cumulonimbus clouds and are consistent with

surface observations of very heavy rainfall, hail, and strong winds. Satellite observations further supported these findings by identifying rapid cloud growth, extremely low cloud-top temperatures, and overshooting tops that coincided temporally with peak radar reflectivity, indicating the presence of very strong updrafts penetrating the upper troposphere.

ERA5 reanalysis results indicate that, although CAPE values were relatively modest, the atmospheric environment was strongly supported by high moisture availability, deep-layer instability, and favorable wind shear, as reflected by elevated SWEAT, KI, and TT values, along with persistently negative LI and SI. The vertical relative humidity profiles demonstrated a transition from strong pre-event moisture gradients to deep-column saturation during the hail occurrence, highlighting the crucial role of vertical moisture transport in sustaining ice particles within the cloud. Overall, this study emphasizes that hail occurrence in tropical urban regions is governed not solely by high CAPE but by the synergistic interaction of moisture-rich layers, deep instability, and organized convective dynamics, underscoring the importance of multi-data integration for operational hail detection and early warning systems.

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