# CHARACTERISTICS OF PUTING BELIUNG PRODUCING CUMULONIMBUS CLOUDS IN INDONESIA: A HIMAWARI-9 SATELLITE DATA ANALYSIS

## Karakteristik Awan Cumulonimbus Penghasil Puting Beliung di Indonesia: Analisis Citra Satelit Himawari-9

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## Abstract

*Puting beliung (PB) is a type of extreme weather phenomenon that often occurs in Indonesia and can cause significant damage to infrastructure, the environment, and human safety. Based on data from the National Disaster Management Agency (BNPB) from 2020 to 2024, the PB phenomenon is an extreme weather phenomenon that ranks second-highest in Indonesia, after floods. The PB phenomenon's high frequency and damaging impact make it important to analyze. In this study, a statistical analysis of Cumulonimbus (Cb) clouds was conducted on several PB cases in Indonesia, by utilizing infrared, visible, and three Red Green Blue (RGB) methods from the Himawari-9 satellite, which aims to explain the characteristics of Cb clouds that contribute to the formation of PB. The resulting analysis from 10 PB cases shows that the existence of consistent characteristics in PB-producing Cb clouds, i.e., cloud top temperatures ranging from -45°C to -80°C, which is consistent with the results of previous PB research, the dominance of ice particle area in the cloud's mature phase, and the presence of strong updrafts in the cloud top. With only a small proportion of those cases showing overshooting the top. These findings indicate that Cb clouds can indeed produce PB phenomena in Indonesia with varying characteristics.*

*Keywords: Puting Beliung, Cumulonimbus, Himawari-9, RGB.*

## Intisari

*Fenomena puting beliung (PB) merupakan salah satu jenis cuaca ekstrem yang kerap terjadi di Indonesia dan dapat menyebabkan kerusakan yang cukup signifikan terhadap infrastruktur, lingkungan, dan keselamatan manusia. Berdasarkan data bencana dari Badan Nasional Penanggulangan Bencana (BNPB) tahun 2020-2024, PB merupakan fenomena cuaca ekstrem yang menempati urutan kedua tertinggi di Indonesia setelah bencana banjir. Frekuensi yang tinggi dan dampak yang merusak menjadikan fenomena PB penting untuk dianalisis. Penelitian ini menganalisis statistik awan Cumulonimbus (Cb) pada beberapa kasus PB di Indonesia dengan memanfaatkan kanal inframerah dan visible dari satelit Himawari-9, serta tiga metode Red Green Blue (RGB) yang bertujuan untuk menjelaskan karakteristik awan Cb yang menghasilkan PB. Hasil analisis terhadap 10 kasus PB menunjukkan adanya karakteristik yang konsisten pada awan Cb penghasil PB, yaitu suhu puncak awan berkisar antara -45°C to -80°C, yang konsisten dengan hasil penelitian PB sebelumnya, dominasi luasan awan berisi partikel es pada fase matang awan, dan keberadaan updraft yang kuat di puncak awan Cb. Hanya sebagian kecil kasus PB menunjukkan adanya overshooting top. Temuan ini mengindikasikan bahwa fenomena PB di Indonesia dapat dihasilkan oleh awan Cb dengan karakteristik yang bervariasi.*

*Kata Kunci: Puting Beliung, Cumulonimbus, Himawari-9, RGB.*

## 1. INTRODUCTION

*Puting beliung* (PB) is a type of extreme weather that often occurs in Indonesia. Based on the occurrence of hydrometeorological disaster data from 2020 to 2024 by the National Disaster Management Agency (BNPB), the occurrence of PB is ranked as the second highest in Indonesia, after flooding (BNPB, 2024). PB is defined as a strong rotating wind generated by Cumulonimbus (Cb) clouds, touching the ground with speeds above 34.8 knots and occurring in a short time, generally less than 10 minutes (BMKG, 2010). This extreme phenomenon can cause significant damage to infrastructure, the environment, and human safety (Lestarianto *et al.*, 2023; Mujiasih *et al.*, 2014). An example of this is a PB event recorded in Rancaekek Sub-district, Bandung Regency, West Java, on February 21, 2024, affecting approximately 835 families, injuring 33 people, and slightly to severely damaging 534 buildings (Saputra, 2024).

Research on PB in Indonesia predominantly adopts observational approaches, utilizing diverse data sources including weather radar, satellite imagery, and both surface and upper-air meteorological observations. This methodology aligns with the global approach for tornado detection and prediction. Since PBs are commonly characterized as small-scale tornadoes (Mujiasih *et al.,* 2014; Yulihastin, 2023), similar analytical frameworks can be applied to their study. On a global scale, weather radar systems are the primary tool for detecting and predicting tornadoes (Veillette *et al.,* 2024). Complementing radar observations, satellite platforms including MODIS, Meteosat Second Generation (MSG) SEVIRI, and Sentinel-2 provide valuable capabilities for trajectory analysis, damage assessment, and post-event reconstruction of tornado occurrences (Burgess *et al.,* 2014; Burow *et al.*, 2020; Kunkel *et al.*, 2023; Mansour *et al.,* 2021; Wang, *et al.*, 2023b).

In Indonesia, the use of weather satellite data, such as Multifunctional Transport Satellite (MTSAT), Himawari-8, Shuttle Radar Topography Mission (SRTM), Landsat, and Quickbird, has also helped in understanding the characteristics of PB. Previous PB studies have shown that PB-producing Cb clouds in Indonesia have frigid cloud-top temperatures, generally below -60°C, estimated through the infrared channel of weather satellite imagery (Agung & Darmawan, 2024; Anam & Amri, 2021; Febrian & Syaiful Amri, 2023; Fernanda *et al.*, 2024). In addition, PB-producing Cb clouds are often supercell and single-cell types (Ali & Hidayati, 2016; Darmawan & Matondang, 2013), with varied shapes such as circles, arcs, and V-shapes (Agung & Darmawan, 2024; Harsa *et al.*, 2011; Lumbangaol & Munandar, 2018; Saragih, 2020). In addition, although weather satellite imagery has been utilized for PB analysis in Indonesia, there is still a gap in understanding the characteristics of Cb clouds that play a significant role in the formation of PB in Indonesia. This research is expected to provide a more in-depth explanation of the characteristics of Cb clouds that produce PB phenomenon.

The RGB method used in this study has several advantages over other satellite image analysis methods, such as single-band analysis, false color composites, and infrared-only methods. These advantages include providing more comprehensive information, being more intuitive for visual interpretation, and effectively combining information from infrared (IR) and visible spectrum (VS) channels. The RGB method has also been successfully applied to analyze other extreme weather phenomena, particularly heavy rainfall events. Research by Dzakiyyurayhan Huda & Mulya (2022) utilized the RGB method to classify convective clouds that cause extreme weather phenomena in Sidoarjo, East Java. Similarly, research by Fadhilah & Mulya (2022) employed the RGB method to analyze the characteristics of convective clouds that trigger flooding in Wamena, Papua.

This research will provide in-depth information on the general statistics of convective clouds that produce tornadoes in Indonesia, while previous PB studies in Indonesia (Harsa *et al.*, 2011; Mujiasih *et al.,* 2014; Silitonga *et al.,* 2017; Siswanto & Supari, 2012; Utama *et al.,* 2019) using satellite analyses have primarily conducted case studies that only examined brightness temperature values and cloud morphological shapes.

The results of this research are expected to contribute positively to understanding the characteristics of PB-producing Cb clouds in Indonesia and serve as a scientific basis for strengthening extreme weather adaptation and mitigation strategies in Indonesia.

## 2. METHODOLOGY

### *2.1 Research Sites*

A total of 10 cases of PB events were analyzed in this study to analyze the characteristics of Cb clouds that produce this phenomenon. PB events data were obtained from Indonesian Agency of Meteorology, Climatology, and Geophysics (BMKG) (BMKG, 2024).

**Table 1.** 10 Selected PB Case Study Used in This Research.

| | PB Cases |
|---|---|
| 1. | South Kalimantan, Hulu Sungai Selatan, Angkinang, 20 June 2022, around 15.00 Local Time (LT) |
| 2. | West Java, Bandung, Rancaekek, 21 Februari 2024, around 15.50 LT |
| 3. | West Kalimantan, Sintang, Tanjung Puri, 16 May 2024, around 16.30 LT |
| 4. | South Kalimantan, Banjar, Sungai Tabuk, 15 September 2022, around 13.15 LT |
| 5. | Bangka Belitung Island, Bangka, Belinyu, Gunung Pelawan, 15 October 2022, around 12.30 LT |
| 6. | South Sumatra, Muara Enim, Gelumbang, Sukajaya, 30 March 2022, around 13.30 LT |
| 7. | East Java, Jombang, Megaluh, 17 January 2024, around 15.30 LT |
| 8. | North Sumatra, Deli Serdang, Percut Sei, 7 May 2024, around 13.30 LT |
| 9. | Central Java, Cilacap, Nusawungu, Jetis, 23 January 2024, around 06.20 LT |
| 10. | West Java, Indramayu, Tukdana, 24 January 2024, around 16.00 LT |

The ten PB cases selected for this study, as presented in Table 1, were based on the most recent occurrence period and represent PB events in the regions of Sumatra, Java, and Kalimantan, which, according to BNPB data, are regions with a higher frequency of tornadoes than other regions in Indonesia.

## 2.2 Data

The weather satellite data used to analyze cloud conditions during a PB event is taken from the Himawari-9 satellite data in Satellite Animation and Interactive Diagnosis (SATAID) format, provided by the BMKG's Database Center. The Himawari-9 satellite, operated by the Japan Meteorological Agency (JMA), is a geostationary satellite that takes pictures of the Earth every 10 minutes with a resolution of 500 m–2 km, and its data can be processed and analyzed using SATAID (Satellite Animation and Interactive Diagnosis) for atmospheric condition analysis and weather monitoring. The data used have been georeferenced and reprojected in latitude-longitude coordinates with a resolution of 0.02° for both the infrared and visible channels. This satellite can produce images for 16 wavelength channels (JMA, 2022). Some channels will be used to analyze cloud characteristics as needed. Satellite data is then processed using Python version 3.11.9 (Foundation, 2001) to obtain single or multiband images in the region around the incident.

## 2.3 Data Processing

Satellite data is then processed to determine the cloud's peak temperature characteristics and reflectivity levels that triggered PB, both spatially and temporally. In addition, the Red Green Blue (RGB) method is used to determine other characteristics of the cloud. The RGB composite method selects multiple spectral channels from satellite data and maps them to the red, green, and blue channels. This process creates a composite image with a broader color spectrum, allowing for better visual interpretation of the satellite data. The RGB methods used in this study are Day Microphysics, Day Convective Storm, and Day Deep Cloud. RGB Day Microphysics is helpful in identifying the constituent particles of Cumulonimbus (Cb) clouds, specifically in the form of water droplets or ice particles (JMA, n.d.). RGB Day Convective Storm is useful for detecting Cb clouds with strong updrafts (JMA, 2020). Meanwhile, RGB Day Deep Cloud is useful for identifying thick clouds, such as Cb clouds with overshooting tops (OT) (JMA, 2016). Details are then presented in Table 2, and this study workflow is presented in Figure 1 below.

**Table 2.** Himawari-9 Channels and RGB Methods Used in This Research.

| Channel/ Product | Himawari-9 Channel (μm) | Analysis performed |
|---|---|---|
| Infrared (IR) | 10.4 | Cloud top temperature estimation |
| Visible (VS) | 0.64 | Analysis of reflectivity level/cloud density |
| RGB *Day Microphysics* | Red: 0.86;<br>Green: 3.9;<br>Blue: 0.4 | Identify the type of Cb cloud-forming content (ice, water, or mixed particles) (JMA, n.d.) |
| RGB *Day Convective Storm* | Red: 7.3-6.2;<br>Green: 10.4-3.9;<br>Blue: 0.64-1.6 | Identification of strong updrafts in Cb clouds (JMA, 2020) |
| RGB *Day Deep Cloud* | Red: 10.4-6.2;<br>Green: 0.64;<br>Blue: 10.4 | Identification of OT in Cb clouds (JMA, 2016) |

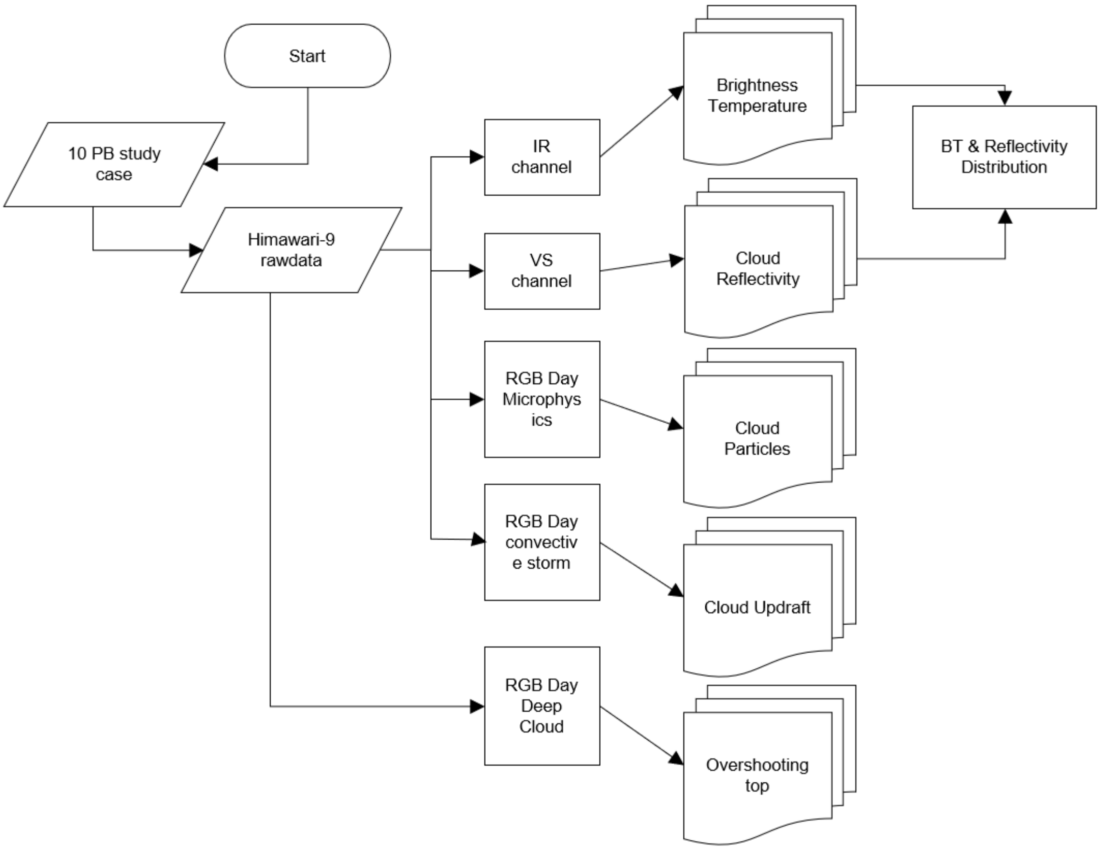


**Figure 1.** Research workflow to investigate the characteristics of PB-producing Cb clouds.

## 3. RESULT AND DISCUSSION

Analysis of PB using weather satellite imagery is expected to result in an understanding of the characteristics of clouds that have the potential to produce the PB phenomenon. The value of cloud statistics is defined as a measurement or parameter used to describe cloud characteristics. The cloud statistics analyzed in the PB event are cloud top temperature, cloud reflectivity, cloud constituent particles, strong updraft identification, and OT.

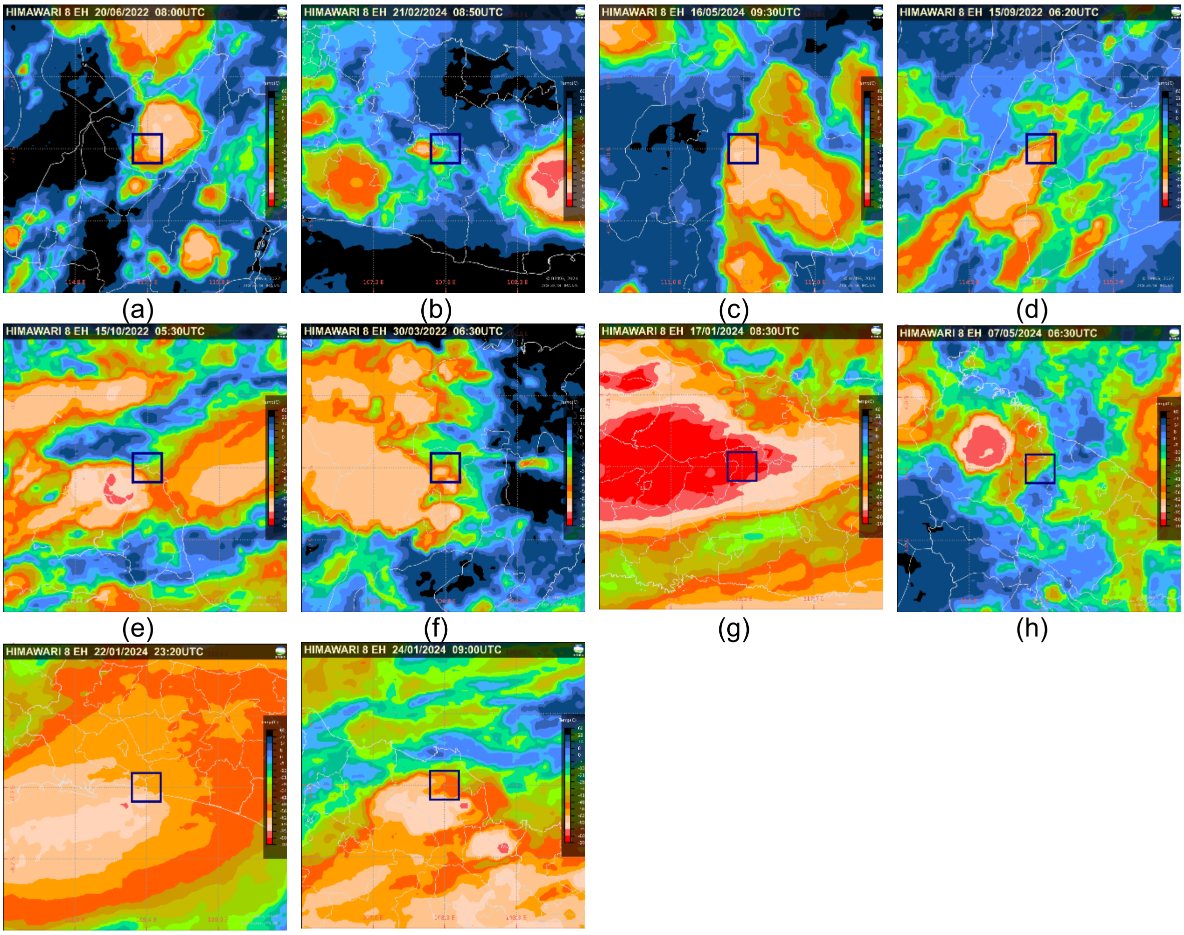
### *3.1 Brightness Temperature*

In the 10 selected PB cases, the brightness temperature (BT) values, as presented in Figure 2, indicate vigorous convective activity. BT values from the 10 PB cases range from -60°C to -80°C, with all PB cases except Rancaekek and Percut Sei showing BT ≤ -70°C. Based on infrared channel observations (10.4μm), when clouds are at the mature stage, BT often decreases significantly, reaching up to -70°C, as observed in PB events in Angkinang, South Kalimantan, and Belinyu, Bangka Belitung Island, and even reaching up to -80°C in Megaluh, Belinyu, and Nusawungu. Meanwhile, PB cases with relatively warm BT (~ -60°C) were observed in Rancakekek, West Java, and Percut Sei, North Sumatra. This condition indicates the growth of convective clouds with high top height, which is one of the characteristics of Cb clouds.

Analysis of brightness temperature (BT) value distribution from the 10 PB case studies during the cloud growth stage reveals variations in thermal characteristics at each study location. Angkinang, Tanjung Puri, and Belinyu exhibit a wide BT range from 10°C to -80°C, indicating intense convective activity with significant vertical cloud development. In contrast, Rancaekek and Sungai Tabuk display a relatively narrow BT range between 15°C and -20°C, suggesting weaker convective activity and limited vertical cloud development compared to other locations. The remaining locations—Gelumbang, Megaluh, Percut Sei, Cilacap, and Indramayu—show diverse BT distributions with ranges from 10°C to -80°C.

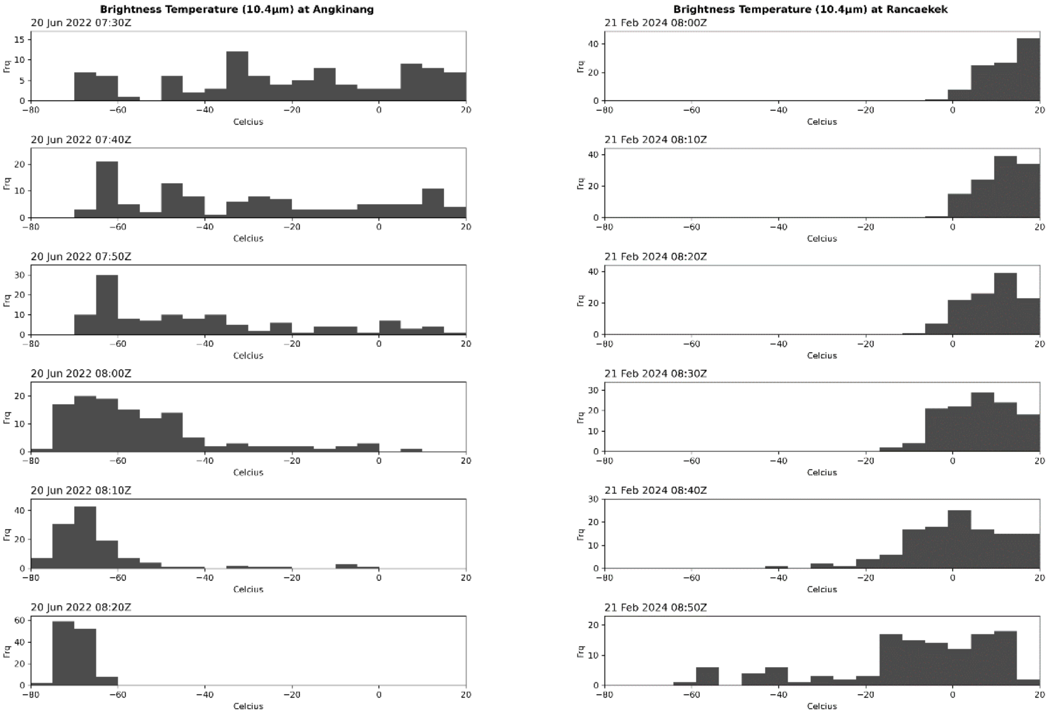
Analysis of BT distribution during the cloud maturity stage across the 10 PB locations shows BT ranges from 20°C to ≤-65°C, indicating stronger convective processes compared to the cloud growth stage. The exception is Percut Sei, where the BT at the maturity stage reaches -50°C, which is relatively warmer than the BT values observed at other locations.

Figure 3 presents BT distribution histograms for (a) the Angkinang PB location and (b) the Rancaekek PB location. BT histograms for the remaining regions are provided in the Appendix.



(a) (b) (c) (d)
(e) (f) (g) (h)
(i) (j)

**Figure 2.** Brightness temperature from the infrared channel (10.4μm); the blue box indicates the PB event location in (a) Angkinang, (b) Rancaekek, (c) Tanjung Puri, (d) Sungai Tabuk, (e) Belinyu, (f) Gelumbang, (g) Megaluh, (h) Percut Sei, (i) Nusawungu, and (j) Tukdana.



(a) (b)

**Figure 3.** Histogram of brightness temperature distribution from the infrared channel (10.4μm) in PB location (a) Angkinang and (b) Rancaekek.

## *3.2 Cloud reflectivity*

In general, from the 10 analyzed PB cases, the cloud reflectivity range values in the mature phase are between 70 - 95%, with 7 cases showing reflectivity > 70%. The maximum reflectivity value of 95% was found in the Belinyu, Bangka Belitung Islands. Some cases also show lower reflectivity values due to the difference in observation time (morning/evening). Thus, solar radiation intensity can be low/high due to this difference. These reflectivity values are also supported by rough cloud textures, which indicate thick convective cloud formations. Figure 4 shows reflectivity images at the 10 PB locations.

Further, cloud reflectivity distribution was analyzed using histograms for the growth and mature stages of convective clouds at all PB locations. In general, the range of cloud reflectivity values at all PB locations during the growth and mature stages is relatively variable. Some locations show an increase in reflectivity, some remain relatively constant, and others show a decrease. However, the magnitude of changes in cloud reflectivity at the 10 PB locations is relatively small, ranging from -5% to 30%. Geographical factors, topography, and local meteorological conditions specific to each location likely influence the diversity of cloud reflectivity values between both stages. Figure 5 shows the distribution of cloud reflectivity at the PB locations of Rancaekek and Tanjung Puri (b), while histograms for the other PB locations are presented in the Appendix (a).

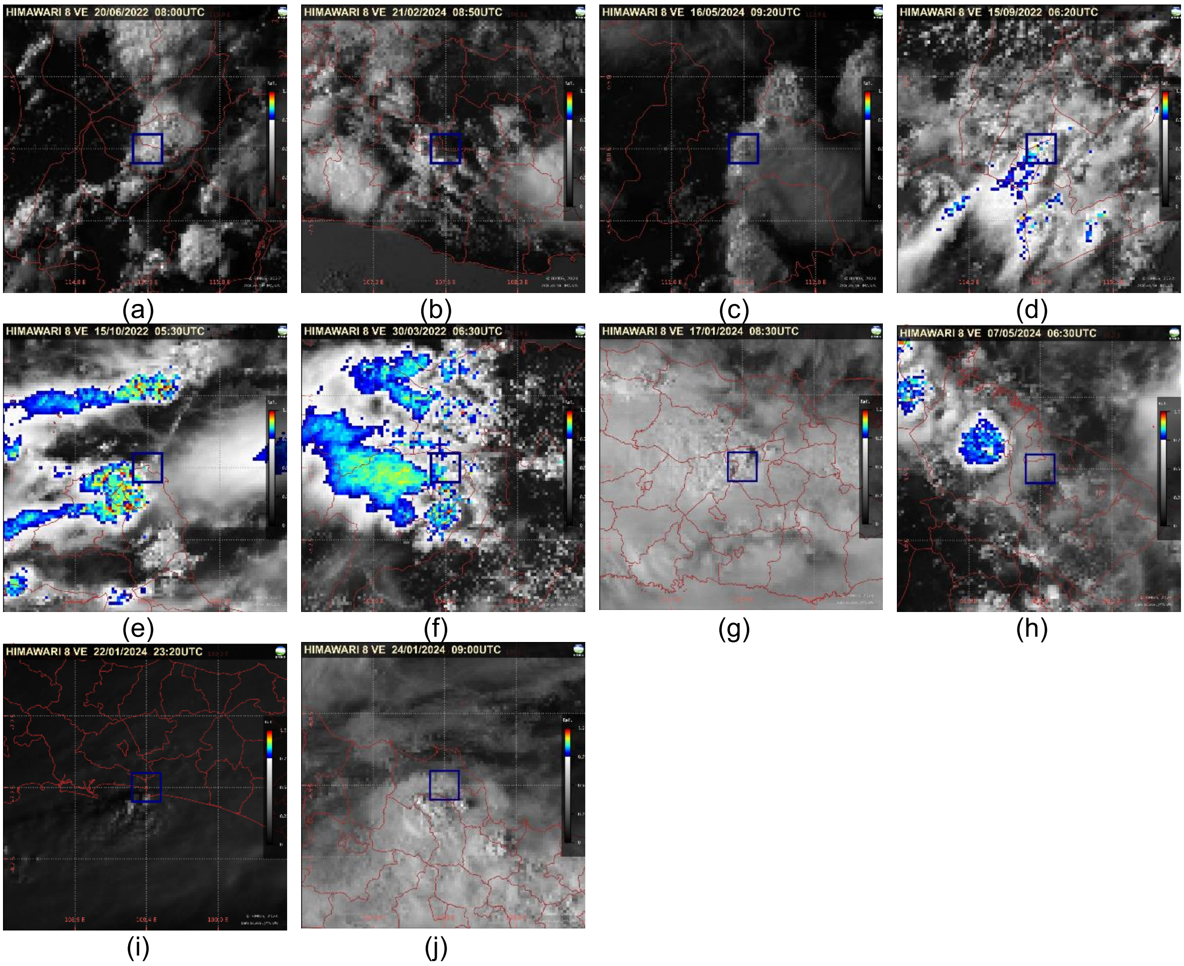
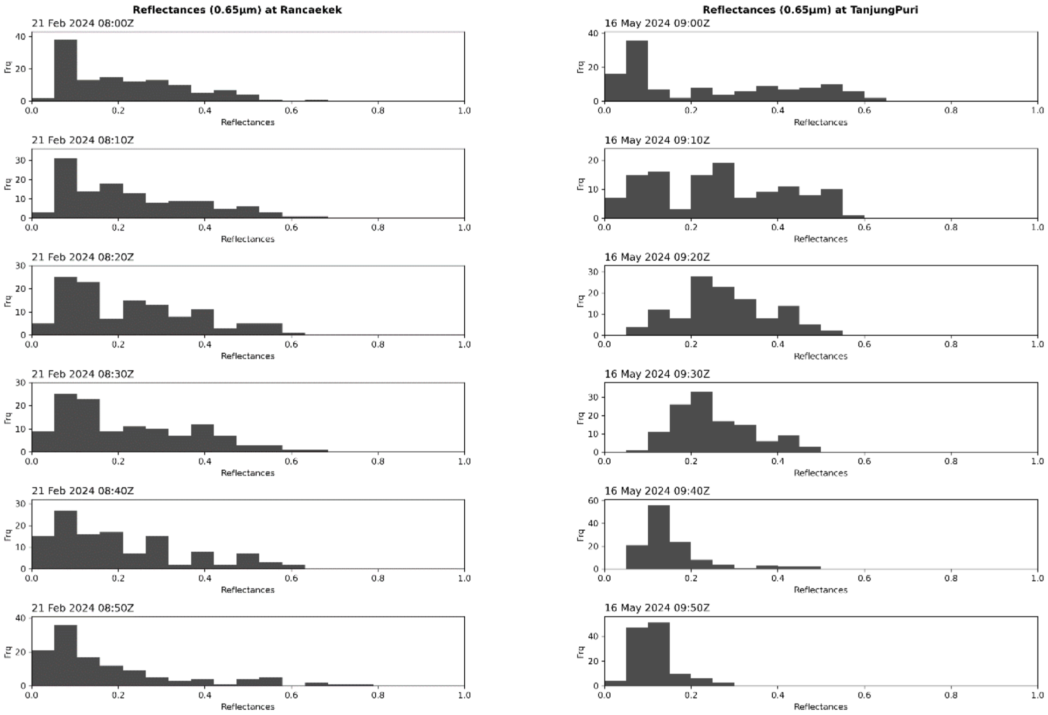


**Figure 4.** Cloud reflectivity from the visible channel (0.65µm); blue box indicating a PB event in (a) Angkinang (b) Rancaekek (c) Tanjung Puri (d) Sungai Tabuk (e) Belinyu (f) Gelumbang (g) Megaluh (h) Percut Sei (i) Nusawungu (j) Tukdana.



(a) (b)

**Figure 5.** Histogram of visible channel values (0.65µm) at the (a) Rancaekek and (b) Tanjung Puri.

## 3.3 Cloud particle type

Ice particles maintain supercell structure, form cold pools through melting processes, and create complex feedback between microphysical processes and storm dynamics, thereby establishing the environmental conditions that favor tornadogenesis (Davies-Jones, 2015). Based on an analysis of the 10 PB cases with the RGB Day Microphysics method, the proportion of the area dominated by ice particles at the top of convective clouds ranges from 30% to 100% of the PB event area represented by the blue box, as in Figures 2 and 4. Note also that all PB cases show extensive ice particles at the cloud's mature development stage. For example, ice content was identified entirely in the PB event area in Megaluh and Nusawungu. However, the Rancaekek PB location showed different results in the RGB Day Microphysics analysis compared to the other nine locations. The analysis revealed various cloud particles, including ice, water, dust, and small particles. Figure 6 shows the RGB Day Microphysics analysis of all PB sites, which are expected to be rich in ice particles and cold water grains at their cloud tops. These conditions indicate towering cloud conditions which have the potential to produce extreme weather phenomena, such as hail and PB.

## 3.4 Strong updraft identification

Strong and sustained updrafts are commonly observed in atmospheric conditions that favor the development of hail-producing storms (Blair *et al.*, 2017). Meanwhile, the initial stage of supercell tornadogenesis requires the formation of a rotating updraft, which creates the mesocyclone (Fischer *et al.*, 2024). The difference in the role of strong updrafts in these two extreme weather phenomena is that hail requires a direct connection with the strongest updraft during peak convective activity, while tornadoes occur through a delayed mechanism in which updrafts strengthen the horizontal vorticity of the environment to form low-level mesocyclones, so that the peak of tornado activity occurs after the peak of convective activity (Wang, *et al.*, 2023a). Strong updrafts were observed at most PB sites, and the ice particle content and vertical growth of convective clouds identified them. From the analysis of 10 PB cases, 7 cases were identified as having strong updrafts at 2% to 50% of the areas in each case, which is depicted with the yellow area, namely in Angkinang, Tanjung Puri, Sungai Tabuk, Gelumbang, Megaluh, Nusawungu, and Tukdana. At Megaluh, strong updrafts were observed almost entirely in the PB area. In Angkinang, Tanjung Puri, and Tukdana, strong updrafts were observed as the clouds entered the mature stage, with roughly 50% of the area showing strong updraft characteristics. In contrast, at the three remaining PB locations, Rancaekek, Belinyu, and Percut Sei, the RGB analysis did not reveal any cloud areas with strong updrafts. The complete results are shown in Figure 7.

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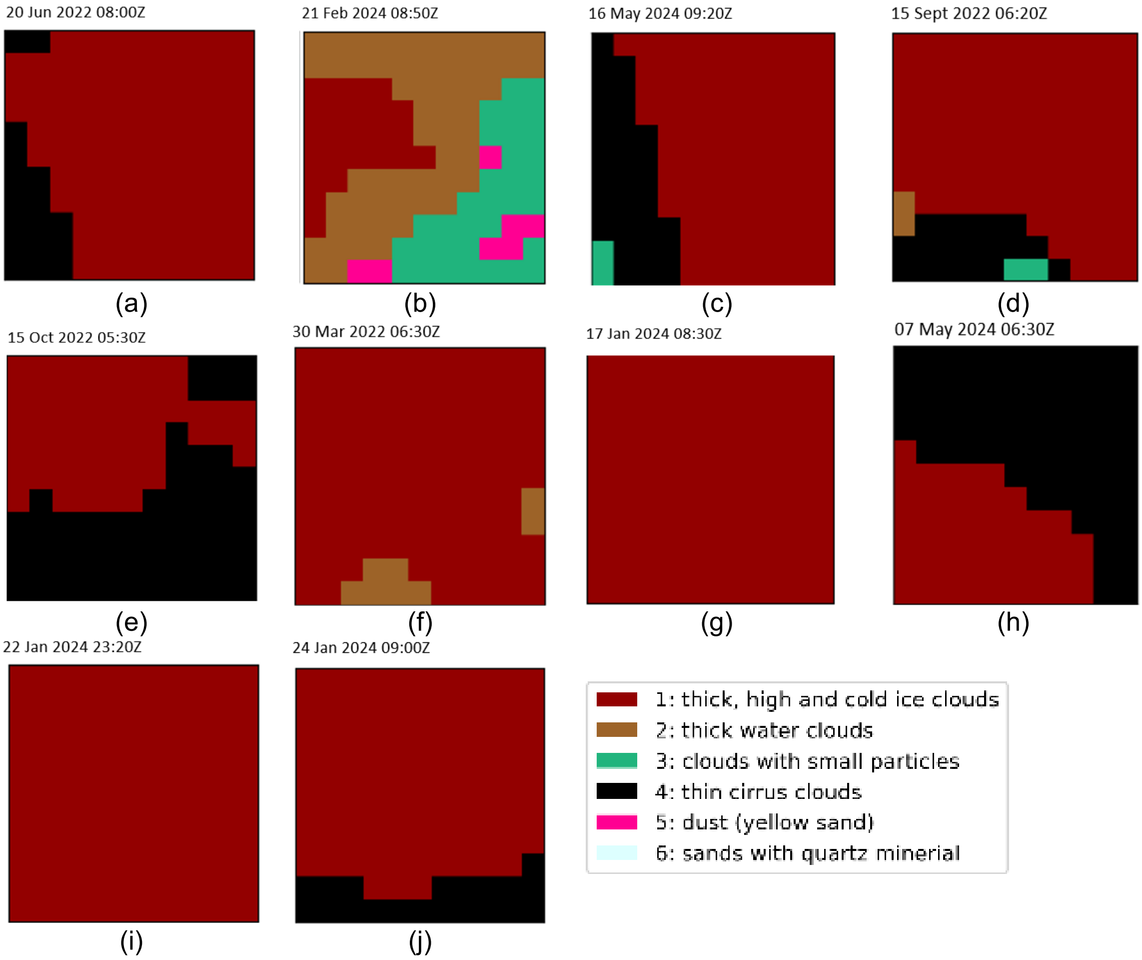

**Figure 6.** RGB Day Microphysics value at the PB location in (a) Angkinang, (b) Rancaekek, (c) Tanjung Puri, (d) Sungai Tabuk, (e) Belinyu, (f) Gelumbang, (g) Megaluh, (h) Percut Sei, (i) Nusawungu, and (j) Tukdana.

## *3.5. Overshooting top identification*

Cloud top feature identification in satellite imagery has long been used to detect severe weather. Flash flooding, massive hail, strong winds, and tornadoes have all been linked to overshooting tops (OT), which are caused by severe deep convection extending into the relatively warm lower stratosphere (Marion *et al*., 2019). Meanwhile, Trapp *et al.* (2017) proposed that OT in satellite images may be utilized in real time to identify storms with substantial updrafts and consequently the highest potential to create severe, devastating tornadoes. This study conducted OT area identification at 10 PB locations using the RGB Day Deep Cloud method. Among the 10 PB cases analyzed, only 3 cases showed OT, ranging from 0% to 7% of the observation area, shown in blue boxes in Figures 2 and 4, namely Sungai Tabuk, Belinyu, and Gelumbang. Though thick clouds were detected, most PB cases did not show an overshooting top. At a PB location in Sungai Tabuk, OT was detected at 13:00 to 13:30 WIB, with high convection intensity also shown. In Belinyu, convective clouds generated overshooting tops starting at 05:20 UTC, which reached a maximum extent of 7% at 05:20 and 05:50 UTC, indicating the formation of Cb clouds with significant OT.

Meanwhile, in Gelumbang, convective activity produced visible OT throughout the entire observation period, achieving maximum coverage of 7% at 06:30 and 06:40 UTC, demonstrating the development of significant Cb clouds. The Cb clouds at this location show extreme vertical growth capable of penetrating the tropopause layer. Figure 8 presents the OT analysis at the 10 PB locations.

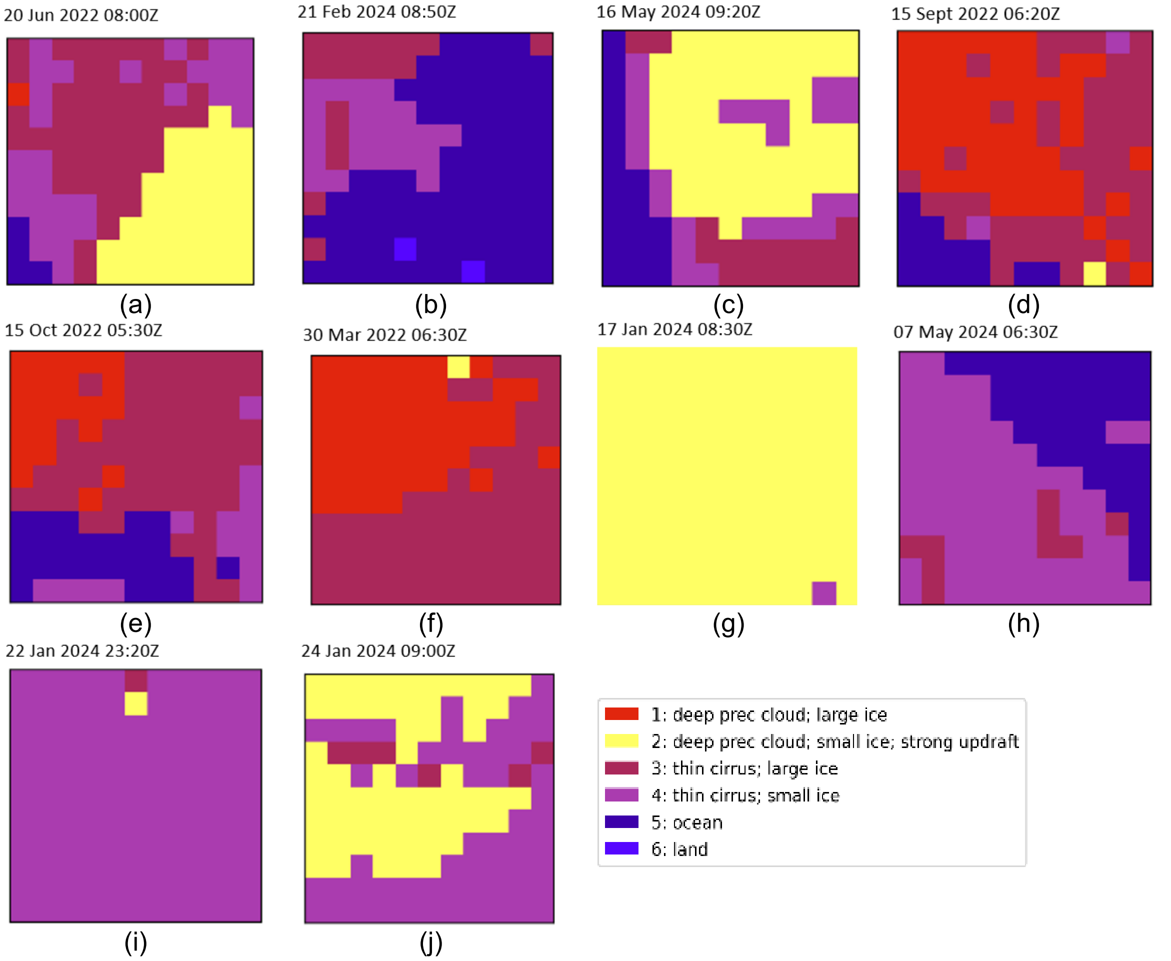

**Figure 7.** RGB Day Convective Storm value at the PB location in (a) Angkinang, (b) Rancaekek, (c) Tanjung Puri, (d) Sungai Tabuk, (e) Belinyu, (f) Gelumbang, (g) Megaluh, (h) Percut Sei, (i) Nusawungu, and (j) Tukdana.

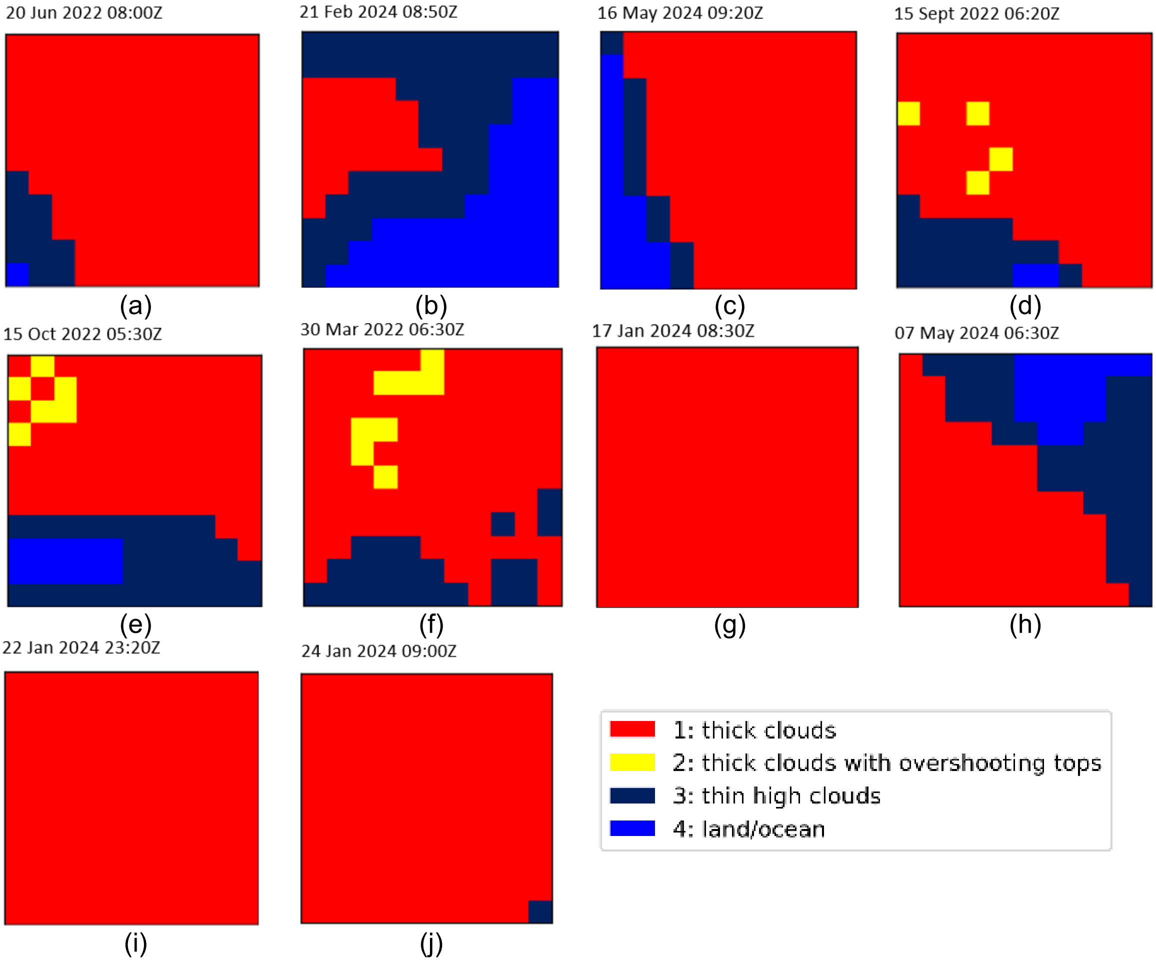

**Figure 8.** RGB Day Deep Clouds value at the PB location in (a) Angkinang, (b) Rancaekek, (c) Tanjung Puri, (d) Sungai Tabuk, (e) Belinyu, (f) Gelumbang, (g) Megaluh, (h) Percut Sei, (i) Nusawungu, and (j) Tukdana.

## 4. CONCLUSION

From the resulting analysis of the 10 PB case studies on PB-producing clouds characteristics, a consistent data pattern, but with certain variations emerge. Brightness temperatures (BT) from the 10 cases were generally frigid, ranging from -45°C to -80°C, with the majority of cases having BT below -60°C, while the cases reflectivity levels varied from 40% to 95%, with the three highest cases reaching more than 90%. The presence of ice particles was also identified in 100% of the cases, confirming the involvement of mature Cb clouds in each PB event. Although 70% of the cases showed strong updrafts, top overshooting was only identified in 30% of the cases, indicating that these two characteristics are not absolute prerequisites for PB. This finding concludes that while there are consistent common characteristics for PB-producing clouds, such as very cold peak temperatures and the presence of ice particles on the cloud tops, PBs can occur at different levels of Cb cloud intensity with variations in their updraft and OT characteristics.

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