



## Characteristics of Quasi-Linear Convective Systems over Bali Based on Weather Radar Observations during January-March 2025

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DOI: <https://doi.org/10.29303/goescienceed.v7i4.3048>

### Article Info:

Received : August, 28 2026  
Revised : September, 11 2026  
Accepted : September, 29 2026  
Published : October, 10 2026

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**Abstract:** Quasi-Linear Convective Systems (QLCSs) are linear convective systems capable of producing significant weather over tropical regions, yet their characteristics over Bali remain poorly documented. This study aimed to identify the spatial and temporal characteristics, formation and dissipation types, propagation, and vertical wind shear (VWS) associated with QLCS events over Bali during January-March 2025 using C-band weather radar observations from BMKG Denpasar. QLCS events were identified based on the Lombardo and Colle criteria, while their characteristics were analyzed using the CMAX, CTR, and VSHEAR products. Six QLCS events were identified during the study period. Most systems initiated over the Coastal Ocean, matured over the Coastal Plain, and dissipated over the Upslope region. The dominant formation types were BB and BA, whereas NU2 was the most frequent dissipation type. Most QLCSs propagated eastward with fast-moving characteristics, while VWS ranged from weak to strong. These findings provide a comprehensive characterization of QLCSs over Bali and offer a useful reference for future weather radar-based studies of tropical maritime convective systems.

**Keywords:** QLCS Formation; System Propagation; Vertical Wind Shear; C-Band Weather Radar; Tropical Convective Systems

**Citation:** Ammarullah, N. A., & Mulya, A. (2026). Characteristics of Quasi-Linear Convective Systems over Bali Based on Weather Radar Observations during January-March 2025. *Jurnal Pendidikan, Sains, Geologi, Dan Geofisika (GeoScienceEd Journal)*, 7(4), 6129–6135. <https://doi.org/10.29303/goescienceed.v7i4.3048>

## Introduction

Indonesia is an archipelagic country located in the tropical maritime region, characterized by high convective activity resulting from the interaction between surface heating, land, and the surrounding oceans. These conditions promote the development of convective clouds, thunderstorms, and various significant weather phenomena that play an important role in rainfall distribution and the atmospheric energy balance. Therefore, understanding the dynamics of convective systems is an important aspect of tropical meteorology research (Aldrian & Dwi Susanto, 2003; Houze, 2014). One of the most common forms of organized convection in the tropics is the Mesoscale Convective System (MCS), which consists of a group of interacting convective cells that develop into a

mesoscale cloud system spanning hundreds of kilometers (Houze, 2004).

One type of MCS that frequently develops in tropical regions is the Quasi-Linear Convective System (QLCS). A QLCS is an elongated, line-shaped convective system characterized by high radar reflectivity and capable of producing heavy rainfall within a relatively short period along its propagation path (Bluestein & Jain, 1985). According to Lombardo & Colle (2010;2012), a system is classified as a QLCS if it has a minimum length of 50 km, a radar reflectivity of at least 35 dBZ with a core reaching 50 dBZ, a length-to-width ratio of approximately 5:1, and a lifetime of at least 30 minutes. Throughout its life cycle, a QLCS undergoes three main phases: initiation, maturity, and dissipation. During the initiation phase, the system may develop through four

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primary formation types: broken line, back building, broken areal, and embedded areal, whereas the dissipation phase generally occurs in either a uniform or non-uniform pattern (Bluestein & Jain, 1985; Lombardo & Colle, 2012). These characteristics indicate that the evolution of a QLCS is influenced by the interaction of various atmospheric processes and therefore requires comprehensive investigation.

Weather radar observations are an effective means of identifying and analyzing QLCS characteristics. Weather radar provides information on reflectivity distribution, convective system structure, and changes in cloud position and intensity at high spatial and temporal resolutions (Houze, 2004); Doviak & Zrnić, 1993). In this study, the Column Maximum (CMAX) product was used to identify QLCS events based on their reflectivity patterns and morphological characteristics, including system length and length-to-width ratio. The Cell Centroid Tracking (CTR) product was used to determine propagation direction and speed, while the Vertical Shear (VSHEAR) product was used to analyze vertical wind shear (VWS) within the 1.5–3.1 km layer (Leonardo, 2018). These radar products provide complementary information for characterizing QLCS development and movement.

Research on QLCS characteristics has evolved from morphological classification of convective systems to radar-based analyses. Bluestein & Jain (1985) introduced a classification of linear convective system formation types, whereas Lombardo & Colle (2010; 2012) developed more objective criteria for QLCS identification based on radar reflectivity parameters and explained the relationship between system evolution and the surrounding atmospheric environment, particularly vertical wind shear. In Indonesia, studies on QLCS characteristics have been conducted in several regions. Meldisa et al. (2019) reported that QLCS events in Pangkalan Bun were dominated by the broken line type with lifetimes ranging from 30 to 60 minutes. The study by Mulya & Maulana (2022) showed that QLCSs in Pontianak generally propagated westward under strong low-level vertical wind shear conditions. Meanwhile, Abubakar et al. (2024) found that most QLCSs in South Sulawesi developed over coastal areas and propagated inland, accompanied by similarly strong vertical wind shear characteristics. These findings indicate that QLCS characteristics may vary among regions due to differences in geographical conditions and local atmospheric dynamics.

Bali Island is one of the regions with geographical conditions that potentially support the development of organized convective systems. The presence of a mountain range extending from west to east, together with its location between the Indian Ocean and the Bali Sea, contributes to the formation of local wind

circulations and convergence that can trigger convective cloud development (Houze, 2014). In addition, the spatial and temporal variability of rainfall over Bali is also influenced by topographic conditions and local atmospheric factors (Setiawan, 2012). Nevertheless, based on previous studies, research on QLCS characteristics in Indonesia remains limited to several regions, including Pangkalan Bun, Pontianak, and South Sulawesi. To date, no study has specifically investigated QLCS characteristics in Bali Province using weather radar data. This condition highlights a research gap that needs to be addressed to improve the understanding of QLCS characteristics in tropical maritime regions with complex topography.

This study focuses on QLCS events during January–March 2025, a period selected because these months fall within the rainy season, when rainfall-producing convection is climatologically active over Bali. This seasonal context provides a relevant basis for examining the organization and evolution of convective systems using weather radar observations (Aldrian & Susanto, 2003; Setiawan, 2012). The study aims to characterize QLCSs over Bali Province through analyses of their spatial and temporal distributions, formation and dissipation types, propagation direction and speed, and vertical wind shear (VWS). The findings are expected to improve understanding of QLCS characteristics in Indonesia's tropical maritime region and provide a reference for future radar-based studies of convective systems.

## Method

This study employed a case study approach combined with a descriptive method to investigate the characteristics of Quasi-Linear Convective Systems (QLCSs) in Bali Province during the January–March 2025 period. The study area was located within the observation range of the Denpasar C-Band Doppler Weather Radar, with a coverage radius of 100 km centered at 8.74° S and 115.18° E. The data used consisted of volumetric weather radar data (.vol) with a temporal resolution of 10 minutes, obtained from the Radar Image Management Subdivision of BMKG. Data processing was performed using the RainDART software, while spatial analysis was conducted using QGIS. The study area was divided into four geographical domains, namely coastal ocean (CO), coastal plain (CP), upslope (UP), and high terrain (HT), following Lombardo & Colle (2010), with elevation boundaries based on Purwadhi et al. (2015). The study area, covering Bali Province and located within the observation range of the Denpasar Weather Radar, is presented in Figure 1.

QLCS events were initially identified using the Column Maximum (CMAX) radar product through visual interpretation of the reflectivity patterns. System

length and width were determined from the observed horizontal extent of each convective system, with the length-to-width ratio used to assess its linear structure. Radar reflectivity was evaluated from the CMAX display, with a minimum reflectivity of 35 dBZ for the system and at least 50 dBZ for its convective core. An event was classified as a QLCS when it met the criteria adopted from Lombardo and Colle (2010; 2012): a minimum system length of 50 km, a length-to-width ratio of 5:1, the specified reflectivity thresholds, and a lifetime of at least 30 minutes. Each identified event was then divided into three developmental phases: initiation, maturity, and dissipation, for subsequent analysis.

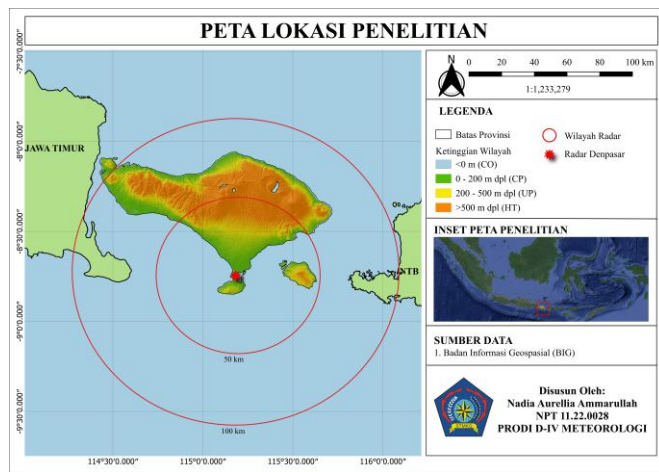


Figure 1. Research Location Map

The spatial characteristics were analyzed based on the event location during each phase of QLCS development. Event locations were mapped into four geographical domains, namely coastal ocean (CO), coastal plain (CP), upslope (UP), and high terrain (HT), and the frequency of occurrence was calculated to determine the dominant location during each developmental phase. Furthermore, the temporal characteristics were analyzed based on the event occurrence time using Local Time (LT), with the time classified into four periods: pre-dawn (01:00-07:00 LT), morning (07:00-13:00 LT), afternoon (13:00-19:00 LT), and evening (19:00-01:00 LT), following Mulya & Maulana (2022), which refers to Lombardo & Colle (2010). This classification was used to identify the temporal distribution of events during each phase and to determine the QLCS lifetime.

The morphological characteristics of QLCSs were analyzed through visual interpretation of reflectivity patterns from the CMAX product. Formation types were

classified into broken line, broken areal, back building, and embedded areal based on Bluestein & Jain (1985). Subsequently, dissipation types were classified into uniform and non-uniform following Lombardo & Colle (2012). This analysis was conducted to identify the evolutionary patterns of QLCSs from the initiation phase through dissipation.

The propagation profile was analyzed using the Cell Centroid Tracking (CTR) product. The analyzed parameters included propagation direction and propagation speed. Propagation direction was determined based on the eight cardinal and intercardinal directions, while propagation speed was classified into slow moving ( $<3 \text{ m s}^{-1}$ ), intermediate moving ( $3\text{--}7 \text{ m s}^{-1}$ ), and fast moving ( $>7 \text{ m s}^{-1}$ ), following Barnes & Sieckman (1984). Vertical Wind Shear (VWS) conditions were analyzed using the VSHEAR product within the 1.5-3.1 km layer, following Basu & Mondal (2002), and were subsequently classified into weak, moderate, and strong based on Chaudhari et al. (2010). All analysis results were then presented in the form of tables, graphs, and maps to illustrate the spatial characteristics, temporal characteristics, formation types, dissipation types, propagation profiles, and VWS conditions of QLCS events in Bali Province.

## Result and Discussion

This section presents the identified Quasi-Linear Convective System (QLCS) events observed over Bali during January-March 2025 based on weather radar observations. The identified events are subsequently analyzed in terms of their spatial and temporal characteristics, formation and dissipation types, propagation profiles, and vertical wind shear (VWS) to provide a comprehensive characterization of QLCSs during the study period.

### Identified QLCS Events

A total of six Quasi-Linear Convective System (QLCS) events were identified within the observation range of the Denpasar Weather Radar during the January-March 2025 period. All events satisfied the QLCS identification criteria adopted in this study, with maximum reflectivity values ranging from 50 to 56 dBZ, system lengths during the maturity phase ranging from 52.61 to 76.20 km, and lifetimes of 40 to 80 minutes. In addition to these fundamental characteristics, Table 1 also presents the spatial and temporal distribution of each event during the initiation, maturity, and dissipation phases.

Table 1. Identified QLCS Events and Their Spatial-Temporal Characteristics during January-March 2025

| No | QLCS Date | Zmax (dBZ) | Length (km) | Lifetime (min) | Spatial Distribution by Phase |     |     | Temporal Distribution by Phase |     |     |
|----|-----------|------------|-------------|----------------|-------------------------------|-----|-----|--------------------------------|-----|-----|
|    |           |            |             |                | Ini                           | Mat | Dis | Ini                            | Mat | Dis |

|   |            |      |       |    |    |    |    |    |    |    |
|---|------------|------|-------|----|----|----|----|----|----|----|
| 1 | 01/01/2025 | 50   | 55,73 | 40 | CO | CO | CO | M  | M  | M  |
| 2 | 19/01/2025 | 51   | 52,61 | 40 | UP | UP | CP | A  | A  | A  |
| 3 | 30/01/2025 | 56   | 66,05 | 60 | CO | CP | CO | PD | PD | PD |
| 4 | 01/02/2025 | 51   | 76,20 | 80 | CO | CO | CO | M  | M  | M  |
| 5 | 19/03/2025 | 55   | 69,93 | 50 | CO | CO | CO | M  | M  | M  |
| 6 | 24/03/2025 | 52,5 | 57,41 | 50 | CP | CP | CP | E  | E  | E  |

**Abbreviations:** Ini, Initiation; Mat, Mature; Dis, Dissipation; CO, Coastal Ocean; CP, Coastal Plain; UP, Upslope; PD, Predawn; M, Morning; A, Afternoon; E = Evening

Based on Table 1, QLCS events during the study period were identified most frequently in January, with three events, while one and two events were recorded in February and March, respectively. Although the number of events was relatively limited, all systems satisfied the predefined criteria for system length, maximum reflectivity, and lifetime. Therefore, all identified events were considered suitable for analyzing QLCS characteristics in this study.

In terms of spatial distribution, most QLCSs initiated over the coastal ocean (CO) domain. Four events remained within the CO domain until the dissipation phase, whereas the other two events shifted toward the coastal plain (CP) domain or vice versa during their life cycle. In addition, one event developed entirely within the CP domain, and another initiated over the upslope (UP) domain before dissipating over the CP domain. No QLCS event was found to initiate over the high terrain (HT) domain during the study period. This pattern indicates that the waters surrounding Bali Island were the dominant region for the initial development of QLCSs during the January-March 2025 period.

Based on the temporal distribution, three QLCS events occurred during the morning (M) period, while

one event each occurred during the pre-dawn (PD), afternoon (A), and evening (E) periods. Notably, each event remained within the same time category from initiation through dissipation. In other words, no event shifted to a different time period during its life cycle. These results indicate that QLCS development during the study period generally occurred within a single local time (LT) interval, with the morning period being the most dominant time of occurrence.

### QLCS Characteristics

Contains the characteristics of each QLCS event during the January-March 2025 period are summarized in Table 2. The table presents the formation type, dissipation type, propagation profile, and Vertical Wind Shear (VWS) values for each identified QLCS event. This summary serves as the basis for analyzing the developmental characteristics of QLCSs over Bali during the study period.

Based on Table 2, the QLCS formation types observed during the January-March 2025 period consisted of two back building (BB) events, two broken areal (BA) events, and one broken line (BL) event. Meanwhile, no embedded areal formation type was identified during the study period.

**Table 2.** Summary of Characteristics of Identified QLCS Events over Bali during January-March 2025

| No | QLCS Date  | Formation Type | Dissipation Type | Propagation Direction |               | Propagation Speed |      | VWS                      |      |
|----|------------|----------------|------------------|-----------------------|---------------|-------------------|------|--------------------------|------|
|    |            |                |                  | Direction             | Compass Point | Speed (m/s)       | Cat. | Value (s <sup>-1</sup> ) | Cat. |
| 1  | 01/01/2025 | BB             | NU 1             | 38                    | NE            | 14,3              | F    | 0,015                    | St   |
| 2  | 19/01/2025 | BB             | NU 2             | 162                   | S             | 1,3               | S    | 0,001                    | Wk   |
| 3  | 30/01/2025 | BA             | NU 2             | 83                    | E             | 14,3              | F    | 0,002                    | Wk   |
| 4  | 01/02/2025 | -              | U                | 26                    | NE            | 17,1              | F    | 0,006                    | St   |
| 5  | 19/03/2025 | BL             | U                | 70                    | E             | 20,9              | F    | 0,001                    | Wk   |
| 6  | 24/03/2025 | BA             | NU 2             | 329                   | NW            | 7,3               | F    | 0,003                    | Md   |

**Abbreviations:** BB, Back Building; BA, Broken Areal; BL, Broken Line; U, Uniform; NU1, Non-uniform 1; NU2, Non-uniform 2; F, Fast Moving; S, Slow Moving; Wk, Weak; Md, Moderate; St, Strong; VWS, Vertical Wind Shear.

In addition, the formation type of the QLCS event on 1 February 2025 could not be identified because the convective system had already developed before entering the observation range of the Denpasar Weather Radar. An example of a back building event is shown in Figure 2. In this formation type, new convective cells continuously develop behind the main system, thereby extending the existing convective structure. This

formation type was identified in the events on 1 January 2025 and 19 January 2025.

Based on Figure 2, new convective cells can be observed developing behind the main system and subsequently merging with the existing system, allowing the linear structure to be maintained throughout the initiation phase. This pattern is consistent with the characteristics of the back building

formation type identified in this study. An example of a broken areal event is shown in Figure 3.

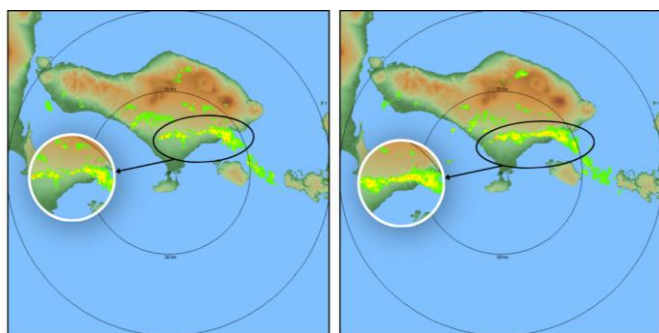


**Figure 2.** Example of a QLCS with a back building formation type on 19 January 2025 at 08:40 LT (left), 08:50 LT (center), and 09:00 LT (right)

In this formation type, the initial convective cells are scattered over an area before developing and merging into an elongated convective system. During the study period, this formation type was identified in the events on 30 January 2025 and 24 March 2025.

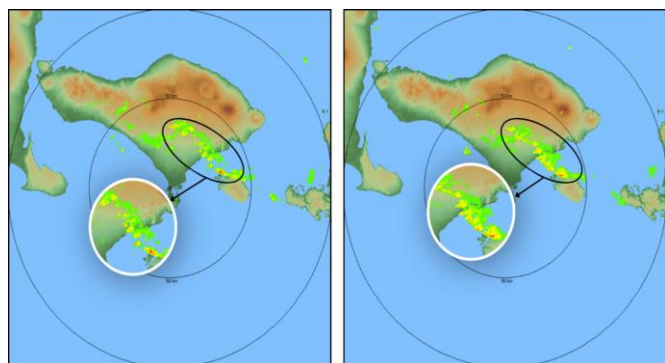


**Figure 3.** Example of a QLCS with a broken areal formation type on 24 March 2025 at 19:00 LT (left) and 19:10 LT (right)

Based on Figure 3, several initially separated convective cells developed and gradually merged to form a more elongated convective structure. This development pattern served as the basis for identifying the broken areal formation type in this event. Meanwhile, an example of a broken line event is shown in Figure 4. This formation type is characterized by convective cells that are initially arranged in an elongated pattern before developing into a more organized QLCS. During the study period, this formation type was identified only in the event on 19 March 2025.

Based on Figure 4, the convective structure exhibited an elongated pattern from the initial stage of development before evolving into a more organized QLCS. These characteristics are consistent with the broken line formation type identified in this study.

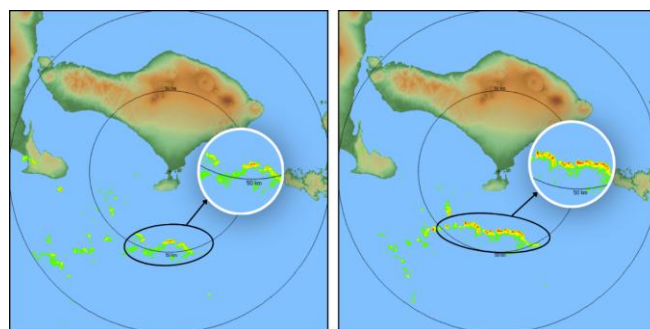


**Figure 4.** Example of a QLCS with a broken line formation type on 19 March 2025 at 08:10 LT (left) and 08:20 LT (right)

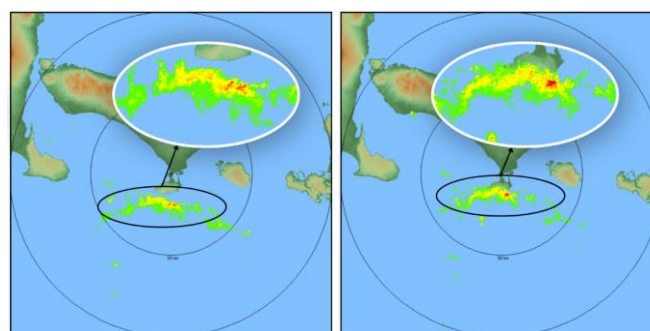


**Figure 5.** Example of a QLCS with a uniform dissipation type on 19 March 2025 at 08:50 LT (left), and 09:00 LT (right)

Based on Table 2, the QLCS dissipation types during the January-March 2025 period were dominated by non-uniform 2 (NU2), with three events, followed by uniform (U), with two events, while non-uniform 1 (NU1) was identified in only one event. These results indicate that most QLCSs during the study period dissipated in a non-uniform manner, implying that the weakening of the system did not occur simultaneously along the convective line. An example of the uniform dissipation type is shown in Figure 5.

Based on Figure 5, reflectivity intensity decreased relatively uniformly along the convective line until the system gradually dissipated. This weakening pattern represents the characteristics of the uniform dissipation type identified in this study. In contrast, an example of the non-uniform dissipation type is shown in Figure 6. In this dissipation type, the weakening of the system occurs unevenly, allowing some convective segments or cores to persist while other parts have already weakened. In this study, non-uniform 2 was the most frequently identified dissipation type, occurring in the events on 19 January 2025, 30 January 2025, and 24 March 2025, whereas non-uniform 1 was identified only in the event on 1 January 2025.

Based on Figure 6, some convective cores maintained relatively high reflectivity, while other parts of the system had already weakened. This condition

indicates that the dissipation occurred unevenly and was therefore classified as the non-uniform 2 dissipation type.

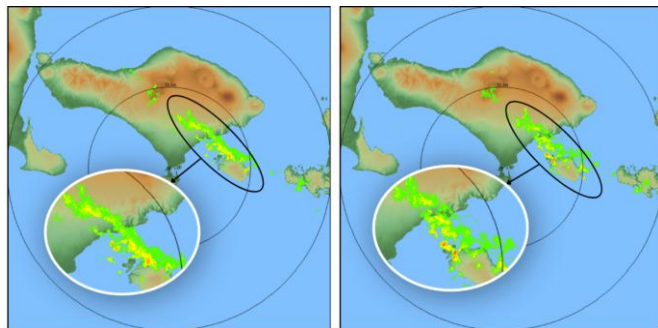


**Figure 6.** Example of a QLCS with a non-uniform 2 dissipation type on 24 March 2025 at 19:30 LT (left), 19:40 LT (right)

The propagation direction and speed of QLCSs during the January-March 2025 period exhibited considerable variability (Table 2). The identified propagation directions were toward the northeast (NE), east (E), south (S), and northwest (NW), with movement predominantly toward the eastern sector (E and NE). In terms of propagation speed, five of the six events were classified as fast moving, while the event on 19 January 2025 was classified as slow moving. The dominance of the fast moving category indicates that most QLCSs during the study period developed as relatively fast-moving convective systems. This pattern is consistent with the findings of Abubakar et al., who reported that QLCS propagation during the rainy season was predominantly classified as fast moving, although the dominant propagation direction in their study tended to be eastward due to the influence of the west monsoon winds.

The VWS values identified during the study period ranged from  $0.001$  to  $0.015 \text{ s}^{-1}$ , with three events classified as weak, one as moderate, and two as strong (Table 2). This variation indicates that QLCSs over Bali during the January-March 2025 period developed under a wide range of vertical wind shear conditions and were not dominated by any single category. In contrast to the findings of Abubakar et al., where the strong category was dominant, the results of this study show a more diverse VWS distribution because the QLCS events occurred under different environmental conditions.

## Conclusion

This study successfully identified six QLCS events over Bali during the January-March 2025 period, exhibiting diverse spatial, temporal, and structural characteristics. Spatially, QLCSs most frequently initiated over the coastal ocean (CO) domain, developed predominantly over the coastal plain (CP) domain

during the maturity phase, and most commonly dissipated over the upslope (UP) domain during the dissipation phase. Temporally, most events initiated in the morning, reached the maturity phase around midday, and dissipated in the afternoon. The identified formation types included back building (BB), broken areal (BA), and broken line (BL), with BB and BA being the most dominant, whereas non-uniform 2 (NU2) was the most frequently observed dissipation type. Most QLCSs propagated toward the eastern sector and were classified as fast moving, while the observed VWS values ranged from weak to strong, indicating that QLCSs developed under diverse low-level vertical wind shear conditions. The findings of this study provide a comprehensive description of QLCS characteristics over Bali during the study period and may serve as a reference for future studies utilizing weather radar data to investigate convective systems in tropical maritime regions.

## Acknowledgements

The authors would like to express their sincere gratitude to the Meteorology Study Program and the College of Meteorology, Climatology, and Geophysics (STMKG) for their support in the completion of this research.

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