Journal of Computation Physics and Earth Science
ISSN: 2776-2521 (online)
Volume 6, Number 1, April 2026, Page 33 - 43
https://journal.physan.org/index.php/jocpes/index

Multiscale Atmospheric Dynamics of Extreme Rainfall Triggering Floods in Bali on 10 September 2025

Abednego Abimanyu[1], Rizk Wahyu Arifin[2], Hafizh Hermanda Putra[3]
[1,2,3]Climatology Program, State College of Meteorology, Climatology and Geophysics, Tangerang, Indonesia

Article Info

Article history:

Received March 31, 2026
Revised April 1, 2026
Accepted April 4, 2026

Keywords:

Extreme Rainfall
Multiscale Atmospheric Dynamics
Bali
Floods

ABSTRACT

This study investigates the multiscale atmospheric dynamics associated with an extreme rainfall event that triggered flooding in Bali on 10 September 2025. A quantitative descriptive approach was applied using ONI, DMI, RMM index, ERA5 reanalysis, Himawari-8 satellite data, and BMKG rainfall observations. Results show that ENSO and IOD were in neutral phases, while the Madden–Julian Oscillation (MJO) was active (RMM amplitude >1), significantly enhancing convective activity over the Maritime Continent. At the regional scale, positive SST anomalies (+0.5–1.5°C), low-level convergence, and strong moisture transport supported upward motion. Local analysis revealed deep convective clouds with cloud-top temperatures below −60°C and rainfall exceeding 100 mm/day. Instability indices showed high K-Index (>35) and moderate CAPE (≈466 J/kg), indicating convection driven by dynamic forcing rather than thermodynamic instability. These findings highlight the dominant role of intraseasonal variability and multiscale interactions in triggering extreme rainfall events in Bali.

Corresponden Author:

Abednego Abimanyu,
Climatology Program, State College of Meteorology, Climatology and Geophysics
Tangerang, Indonesia
Email: abednegoabimanyu@gmail.com

1. INTRODUCTION

Extreme rainfall is one of the most frequent hydrometeorological hazards in Indonesia, often resulting in flooding, landslides, and substantial socio-economic impacts. This condition is closely linked to the unique characteristics of the Maritime Continent, which is widely recognized as one of the most active convective regions in the world. The combination of warm sea surface temperatures, complex topography, and strong air–sea interactions makes rainfall in this region highly variable in both space and time [1]–[3].

Rainfall over the Maritime Continent is not controlled by a single factor, but rather by the interaction of atmospheric processes across multiple scales. At the global scale, large-scale climate variability such as the El Nino–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) plays an important role in shaping rainfall patterns by altering atmospheric circulation and sea surface temperature distribution [4], [5]. However, several studies have pointed out that extreme rainfall events can still occur even when ENSO and IOD are in neutral conditions, suggesting that other mechanisms also play a significant role [6].

One of the key drivers at the intraseasonal scale is the Madden–Julian Oscillation (MJO). This phenomenon is known to strongly influence tropical convection as it propagates across the Indian Ocean and the Maritime Continent. When the active phase of the MJO reaches this region, it enhances moisture convergence and vertical motion, which in turn promotes the development of deep convection and increases rainfall intensity [7]–[9]. In fact, previous studies have shown that the presence of an active MJO can significantly increase the likelihood of extreme rainfall events in Southeast Asia [10], [11].

At a more regional scale, monsoon circulation and synoptic-scale systems also contribute to rainfall variability. Wind patterns, especially low-level convergence and moisture transport, are essential in supplying water vapor and triggering upward motion that supports convective processes. In addition, warmer sea surface temperatures can intensify evaporation, increasing atmospheric moisture and further strengthening convection [12]–[14].

At the local scale, the intensity of rainfall is closely related to atmospheric instability and cloud development processes. Parameters such as CAPE, K-Index, and Total Totals Index are commonly used to evaluate the potential for convection. However, recent findings suggest that strong convection in tropical regions does not always require high thermodynamic instability. Instead, dynamic factors such as large-scale moisture convergence and atmospheric wave activity can play a more dominant role in triggering extreme rainfall [15], [16]. Satellite observations, particularly from Himawari-8, have also been widely used to monitor cloud-top temperatures and identify deep convective systems associated with heavy rainfall events [17].

Although many studies have examined rainfall variability over the Maritime Continent, most of them tend to focus on either large-scale climate drivers or local atmospheric conditions separately. As a result, the interaction between processes at different scales is still not fully understood, especially for specific extreme rainfall events in regions such as Bali.

Therefore, this study aims to analyze the multiscale atmospheric processes associated with an extreme rainfall event that occurred in Bali on 10 September 2025. By integrating global climate indices, regional atmospheric dynamics, and local convective characteristics, this study seeks to provide a more comprehensive understanding of the mechanisms behind extreme rainfall. The results are expected to support the improvement of early warning systems and contribute to a better understanding of multiscale interactions in tropical meteorology.

2. RESEARCH METHOD

2.1. Study Area

The study was conducted in Bali Province, Indonesia, located between 08°03′40″ – 08°50′48″ South Latitude and 114°25′53″ – 115°42′40″ East Longitude. Bali covers an area of approximately 5,780 km² and consists of eight regencies and one city. Geographically, it is bounded by the Bali Sea to the north, the Bali Strait to the west, the Indian Ocean to the south, and the Lombok Strait to the east. This geographical setting strongly influences Bali through tropical atmospheric and oceanic interactions, which play a crucial role in regional weather variability.

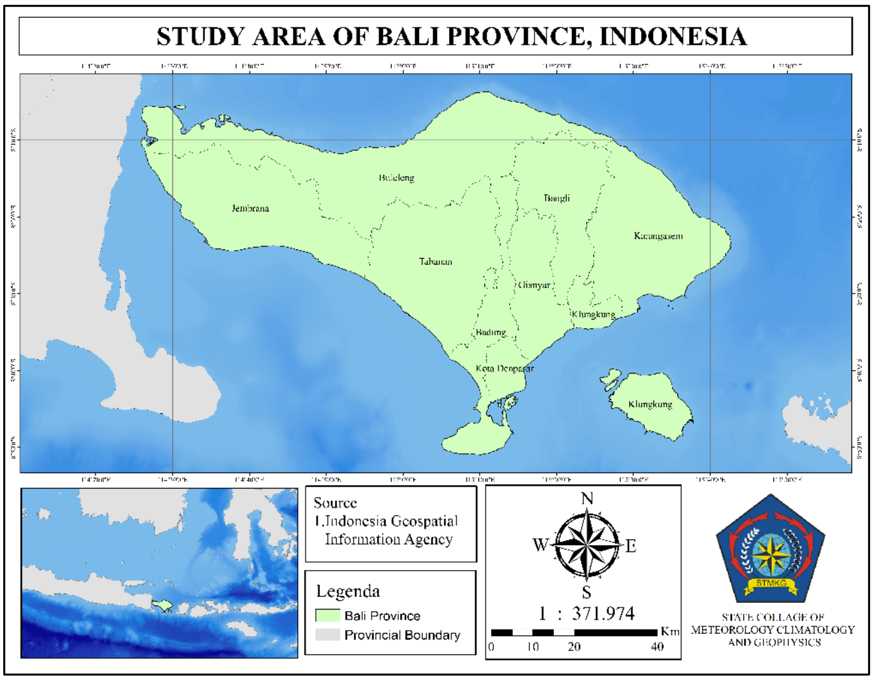

Fig. 1 Study area of Bali Province, Indonesia

2.2. Data

This study utilized a combination of atmospheric, oceanographic, and observational datasets to analyze extreme rainfall events across multiple scales. The integration of multi-source datasets is essential for understanding atmospheric processes from global to local scales.

The datasets used include:

- Oceanic Nino Index (ONI) is used to identify ENSO phases based on sea surface temperature anomalies, which influence rainfall variability over Indonesia [2].
- Dipole Mode Index (DMI) is applied to assess the Indian Ocean Dipole (IOD), which modulates rainfall distribution through sea surface temperature gradients in the Indian Ocean [3].
- Real-time Multivariate MJO (RMM) index is utilized to analyze intraseasonal variability and convective activity associated with the Madden–Julian Oscillation (MJO) [4].
- Australian Monsoon Index (AUSMI) and Western North Pacific Monsoon Index (WNPMI), derived from zonal wind at 850 hPa, are used to evaluate the influence of monsoon circulation on regional atmospheric dynamics [6].
- ERA5 reanalysis data from ECMWF, including zonal wind (u), meridional wind (v), specific humidity (q), and Mean Sea Level Pressure (MSLP), are used to analyze atmospheric circulation, divergence, and moisture transport. The dataset has a spatial resolution of 0.25° × 0.25° with hourly temporal resolution, allowing detailed representation of synoptic-scale conditions [7].
- Himawari-8 infrared satellite imagery (Band 13) is used to analyze cloud-top temperature (CTT) and convective cloud evolution, which are closely related to rainfall intensity and deep convection processes [8].
- Rainfall observation data from BMKG stations are used to validate precipitation intensity and characterize the temporal distribution of the extreme rainfall event.

2.3. Research Tools

- Climate Data Operators (CDO) for processing NetCDF data
- Grid Analysis and Display System (GrADS) for atmospheric visualization
- Satellite Animation and Interactive Diagnosis (SATAID) for cloud analysis
- Python for statistical analysis and data visualization
- ArcGIS for spatial mapping
- Microsoft Excel for basic data processing

2.4. Methodology

This study applies a multiscale diagnostic approach combining dynamical and thermodynamical analysis to investigate the atmospheric conditions associated with an extreme rainfall event in Bali on 9 September 2025. The analysis focuses specifically on this event (H0) to capture the atmospheric state during peak rainfall occurrence.

At the global scale, climate variability is analyzed using the Oceanic Nino Index (ONI) to represent El Nino–Southern Oscillation (ENSO), the Dipole Mode Index (DMI) for the Indian Ocean Dipole (IOD), and the Real-time Multivariate Madden–Julian Oscillation (RMM) index. ENSO and IOD influence rainfall variability through sea surface temperature anomalies and large-scale circulation changes [2], [3], while the MJO enhances convective activity when active (RMM ≥ 1) [4], [5].

At the regional scale, synoptic atmospheric conditions are examined using ERA5 reanalysis data from ECMWF with a spatial resolution of 0.25° × 0.25° and hourly temporal resolution. The parameters analyzed include sea surface temperature (SST) anomalies, wind patterns at 850 hPa, Mean Sea Level Pressure (MSLP), monsoon indices (AUSMI and WNPMI), low-level moisture transport (LLMT), and wind divergence. These variables are essential for identifying moisture supply, atmospheric convergence, and vertical motion that support convective development [6], [7].

At the local scale, convective activity is analyzed using Himawari-8 satellite infrared imagery to evaluate cloud-top temperature (CTT) and cloud evolution. Deep convective clouds are identified by CTT values below −60°C, which indicate the presence of cumulonimbus clouds associated with heavy rainfall [8]. Atmospheric instability is further assessed using thermodynamic indices, including Convective Available Potential Energy (CAPE), K-Index, and Total Totals Index, to evaluate the potential for convective development. The classification criteria for these indices follow established thresholds [9], where higher values indicate more favorable conditions for deep convection [10].

Finally, all atmospheric parameters are integrated with rainfall observations from the Meteorology, Climatology, and Geophysics Agency (BMKG) to validate precipitation intensity and to establish the relationship between multiscale atmospheric dynamics and the observed extreme rainfall event on 9 September 2025.

Table 1. Rainfall Intensity Classification [11]

Rainfall Intensity	Rainfall Amount (mm/day)	Category
Light Rainfall	< 20 mm/day	Light
Moderate Rainfall	20 – 50 mm/day	Moderate
Heavy Rainfall	50 – 100 mm/day	Heavy

Rainfall Intensity	Rainfall Amount (mm/day)	Category
Extreme Rainfall	> 100 mm/day	Extreme

Table 2. Criteria of Atmospheric Instability Indices [9]

Index	Value Range	Category / Interpretation
CAPE (J/kg)	0	Stable
	0 – 1000	Slightly Unstable
	1000 – 2500	Moderately Unstable
	2500 – 3500	Highly Unstable
	> 3500	Extremely Unstable
K-Index	< 20	Weak
	20 – 35	Moderate
	> 35	Strong
Total Totals Index	44	Thunderstrom
	50	Strong Thunderstorm
	> 50	Severe Convective Potential (Tornado)

3. RESULT AND DISCUSSION

3.1. Global-Scale Analysis

The global-scale analysis indicates that ENSO and IOD were in neutral conditions during 9 September 2025. This is clearly shown in Fig. 2, where the Oceanic Nino Index (ONI) fluctuates around zero, indicating the absence of El Nino or La Nina influence. Similarly, Fig. 3 shows that the Dipole Mode Index (DMI) remains near neutral values, suggesting that the Indian Ocean Dipole did not significantly modulate rainfall over Indonesia during this period.

In contrast, the Madden–Julian Oscillation (MJO) exhibits a different behavior. As shown in Fig. 4, the MJO phase diagram indicates that the convective signal was active over the Maritime Continent, with an amplitude greater than 1. This condition reflects enhanced large-scale convection and is typically associated with increased moisture convergence and upward motion.

The contrast between neutral ENSO–IOD conditions and an active MJO suggests that intraseasonal variability played a more dominant role than interannual variability in this event. This result is consistent with previous findings showing that MJO phases 4–5 significantly enhance rainfall over the Maritime Continent through strengthened large-scale ascent and moisture convergence [4].

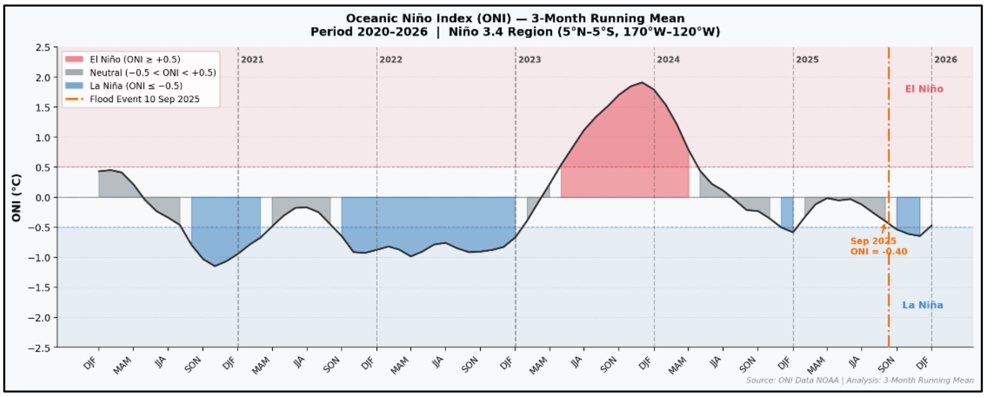

Fig. 2 Time series of Oceanic Nino Index (ONI) indicating ENSO conditions during the study period

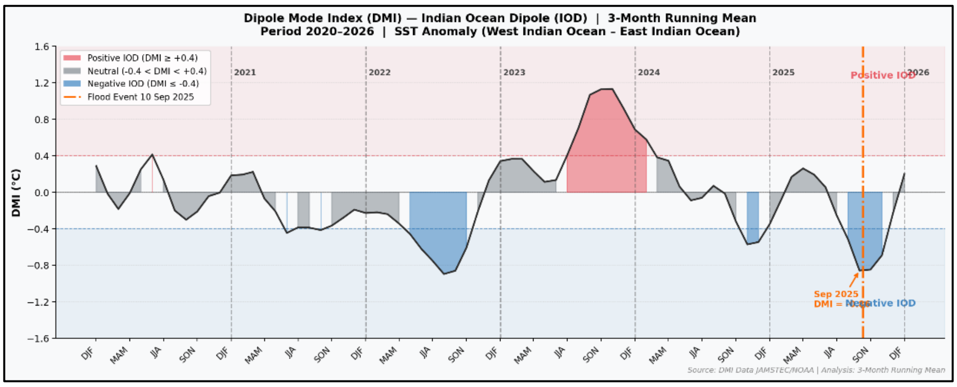

Fig. 3 Time series of Dipole Mode Index (DMI) representing Indian Ocean Dipole (IOD) conditions

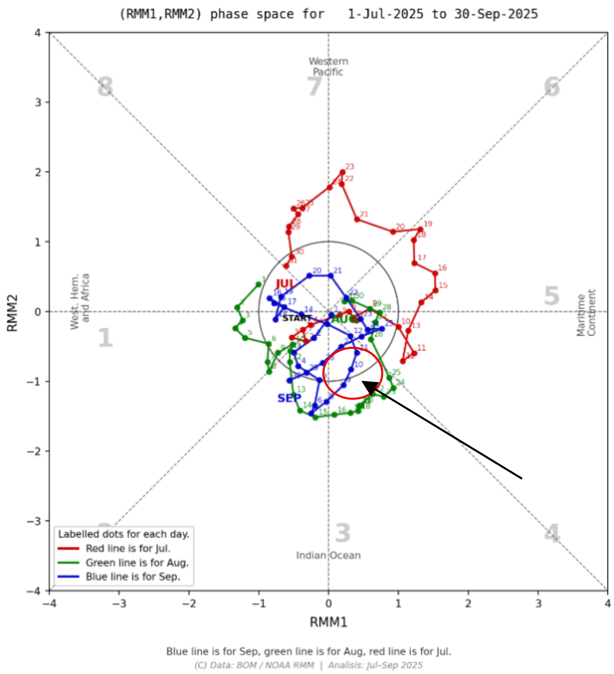

Fig. 4 Phase diagram of Madden–Julian Oscillation (MJO) based on RMM index showing active convection over the Maritime Continent

3.2. Regional-Scale Analysis

At the regional scale, the atmospheric conditions during the event show a coherent interaction between oceanic and atmospheric variables.

As presented in Fig. 5, positive sea surface temperature (SST) anomalies ranging from approximately +0.5 to +1.5°C are observed around the Indonesian region. These warmer SSTs likely enhanced surface evaporation, increasing the availability of moisture in the lower atmosphere. The role of this moisture is further reflected in Fig. 6, where wind vectors at 850 hPa indicate low-level convergence over Bali. This convergence implies the accumulation of moist air, which is a key driver of upward motion. Supporting this, Fig. 7 shows relatively low Mean Sea Level Pressure (MSLP) over the region, indicating a favorable environment for rising air motion.

Moisture supply is further confirmed by Fig. 8, which illustrates strong low-level moisture transport (LLMT) toward Bali. This continuous influx of water vapor provides the necessary energy for sustained convective processes. In addition, Fig. 9 shows negative divergence values (i.e., convergence), reinforcing the presence of upward motion in the lower atmosphere. The role of large-scale circulation is also evident from the monsoon indices. Fig. 10 (AUSMI) and Fig. 11 (WNPMI) indicate active monsoonal flow, which likely contributed to the transport of moisture from surrounding oceans into the Indonesian region.

Overall, these figures demonstrate that the interaction between SST anomalies, low-level convergence, and moisture transport enhanced latent heat release, which strengthened upward motion and maintained convective development during the event.

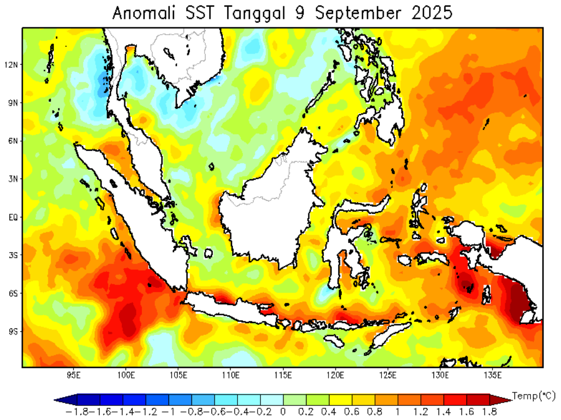

Fig. 5 Spatial distribution of sea surface temperature (SST) anomalies over the Indonesian region

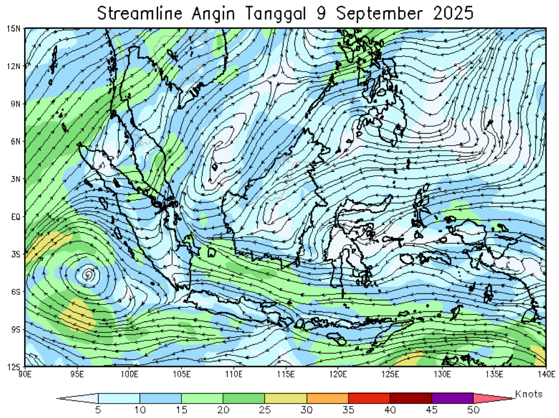

Fig. 6 Wind vector at 850 hPa showing low-level convergence over Bali

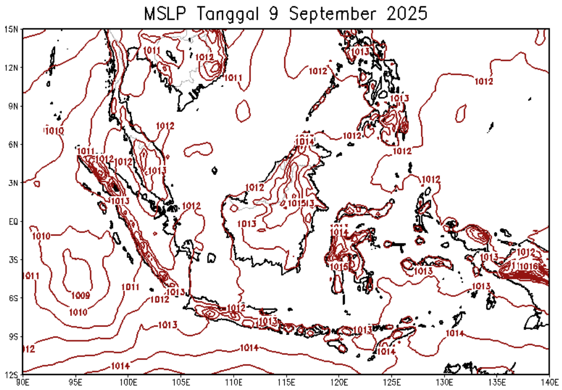

Fig. 7 Mean Sea Level Pressure (MSLP) indicating low-pressure systems over the study area

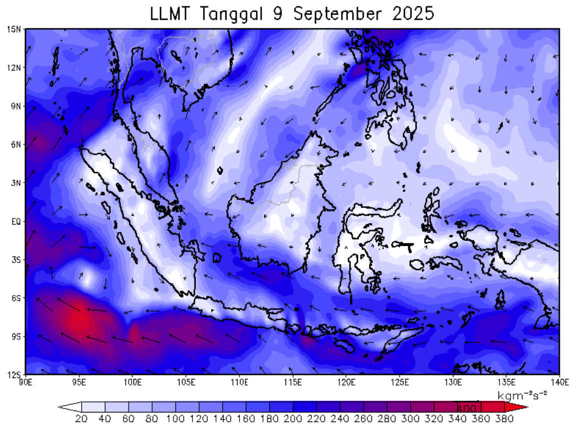

Fig. 8 Low-Level Moisture Transport (LLMT) showing moisture flux toward Bali

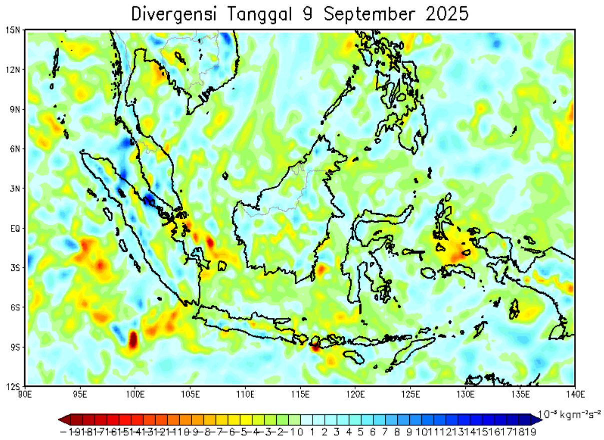

Fig. 9 Wind divergence at 850 hPa indicating convergence zones over Bali

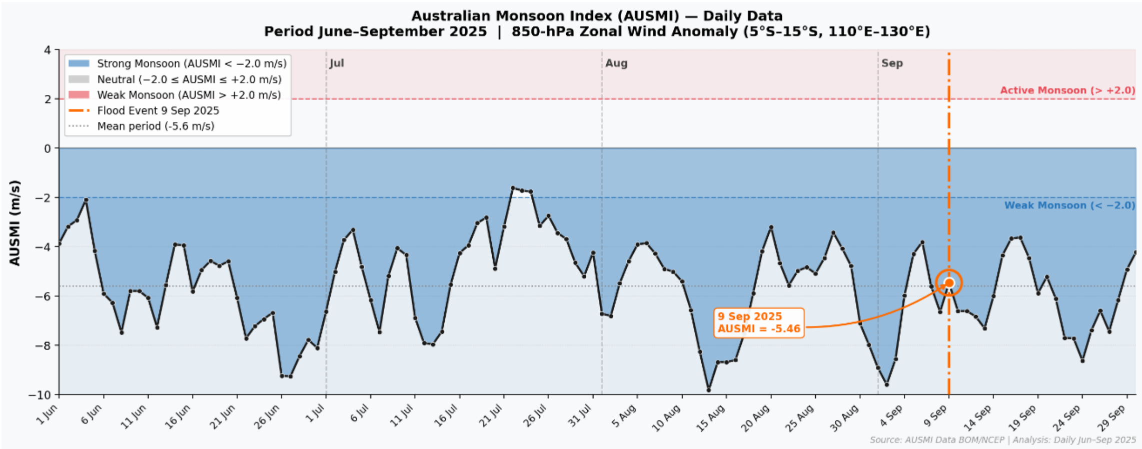

Fig. 10 Time series of Australian Monsoon Index (AUSMI) indicating the variability of monsoon circulation over the Australian region during the study period

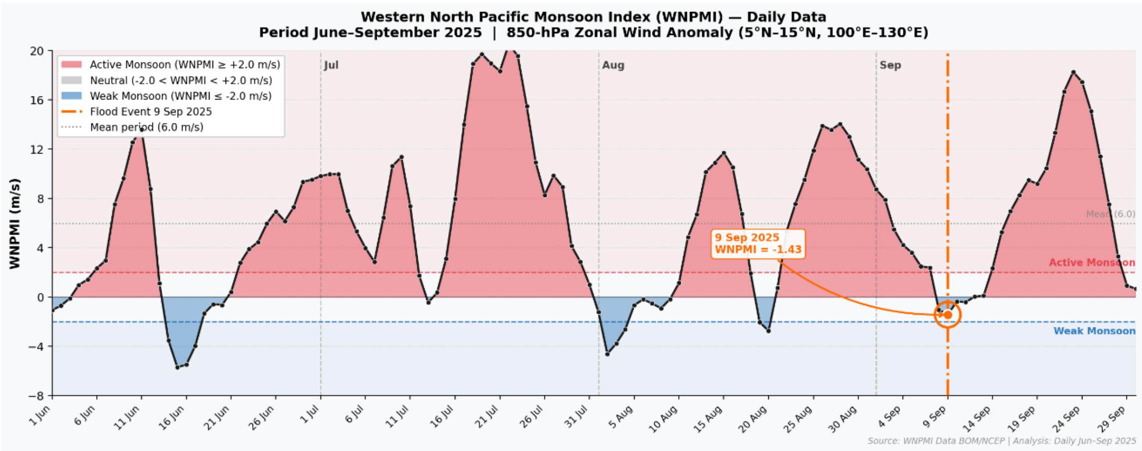

Fig. 11 Time series of Western North Pacific Monsoon Index (WNPMI) representing monsoon activity influencing moisture transport toward the Indonesian region

3.3. Local-Scale Analysis

At the local scale, satellite observations provide clear evidence of deep convective activity. As shown in Fig. 12, cloud-top temperatures (CTT) drop below −60°C over Bali, indicating the presence of deep cumulonimbus clouds. These cloud characteristics are typically associated with intense rainfall.

The temporal evolution of convection is further illustrated in Fig. 13, where all observed regions (Jembrana, Gianyar, Badung, and Tabanan) show a consistent decrease in CTT, indicating the growth and persistence of deep convection during the event.

However, when examining the thermodynamic conditions in Table 3, a different picture emerges. CAPE values range from only 8.36 to 466.04 J/kg, which fall into stable to weak instability categories. This indicates that the atmospheric environment was not strongly supportive of convection from a thermodynamic perspective.

In contrast, the K-Index values exceed 35, indicating strong potential for convective activity, while the Total Totals Index remains in the moderate range. The spatial distribution shown in Fig. 13 (instability maps) also confirms that instability is not uniformly high across Bali.

This apparent contradiction suggests that convection during this event was not primarily driven by thermodynamic instability. Instead, strong dynamic forcing—such as low-level moisture convergence and MJO-induced large-scale ascent—played a more dominant role.

This interpretation is further supported by Fig. 14, which shows that daily rainfall exceeded 100 mm/day in several areas, classifying the event as extreme rainfall. The occurrence of such intense rainfall under marginal CAPE conditions highlights that extreme convection in tropical regions can be triggered even when instability is relatively weak, as long as strong dynamical forcing is present.

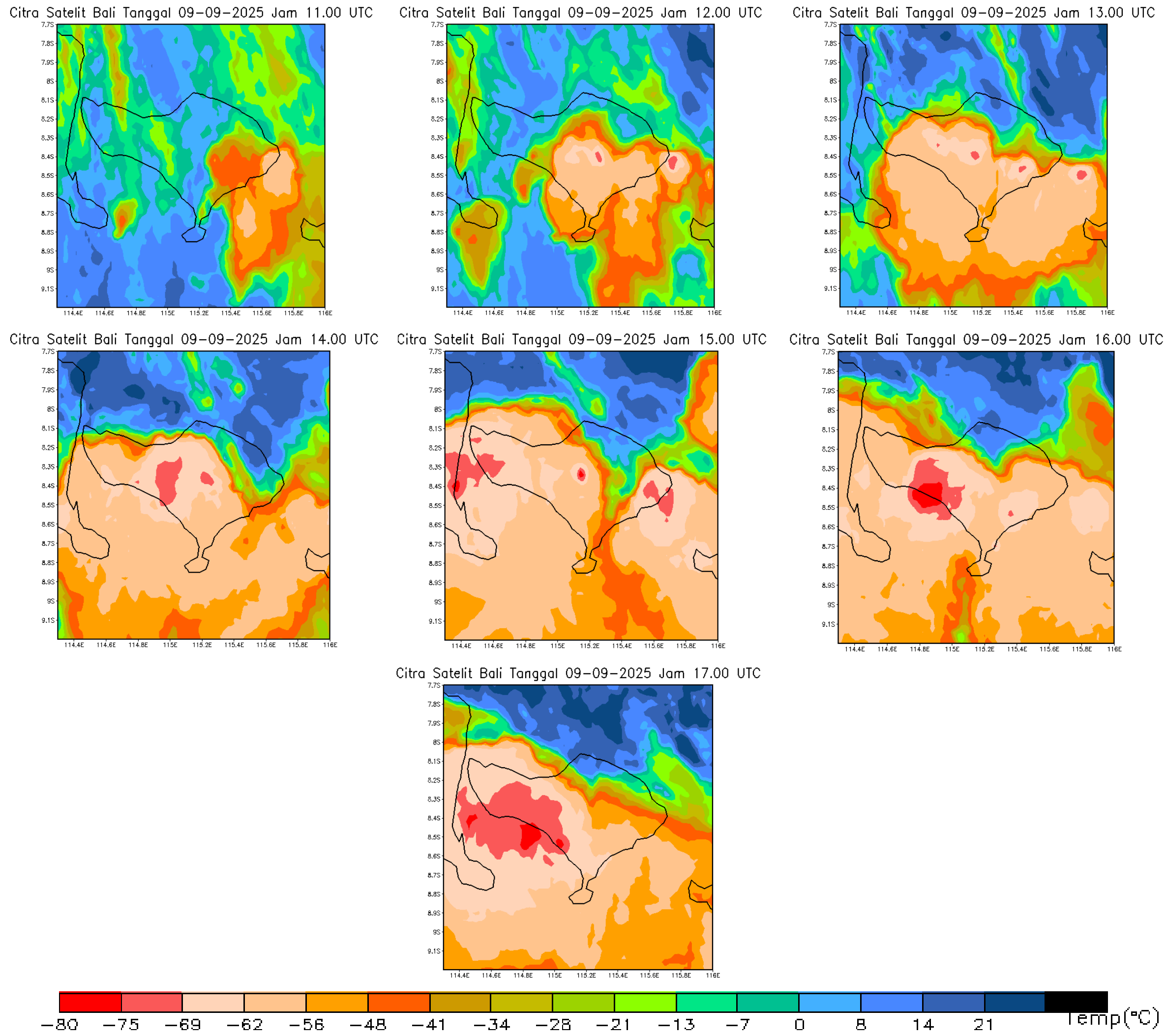

Fig. 12 Himawari-8 infrared imagery showing cloud-top temperature distribution during the event

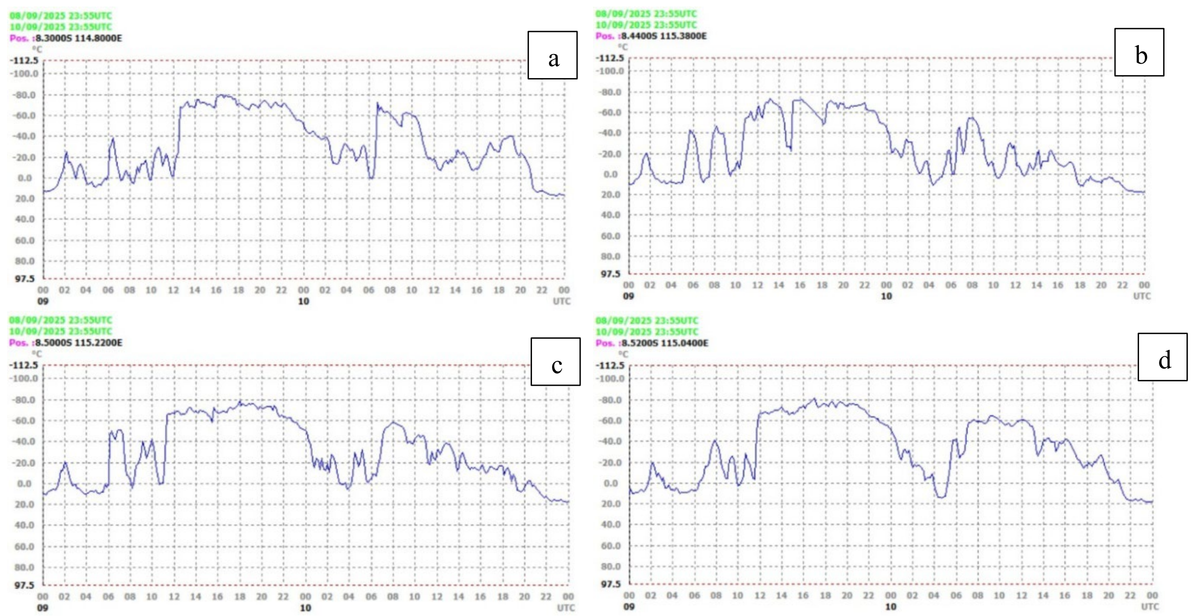

Fig. 13. Time series of cloud-top temperature (CTT) at four affected regions: Jembrana (a), Gianyar (b), Badung (c), and Tabanan (d)

Table 3. Instability Indices Bali

Index	Value on 00.00 UTC	Value on 12.00 UTC
CAPE (J/kg)	8.36	466.04
K-Index	35.30	39.40
Total Totals Index	43.20	46.00

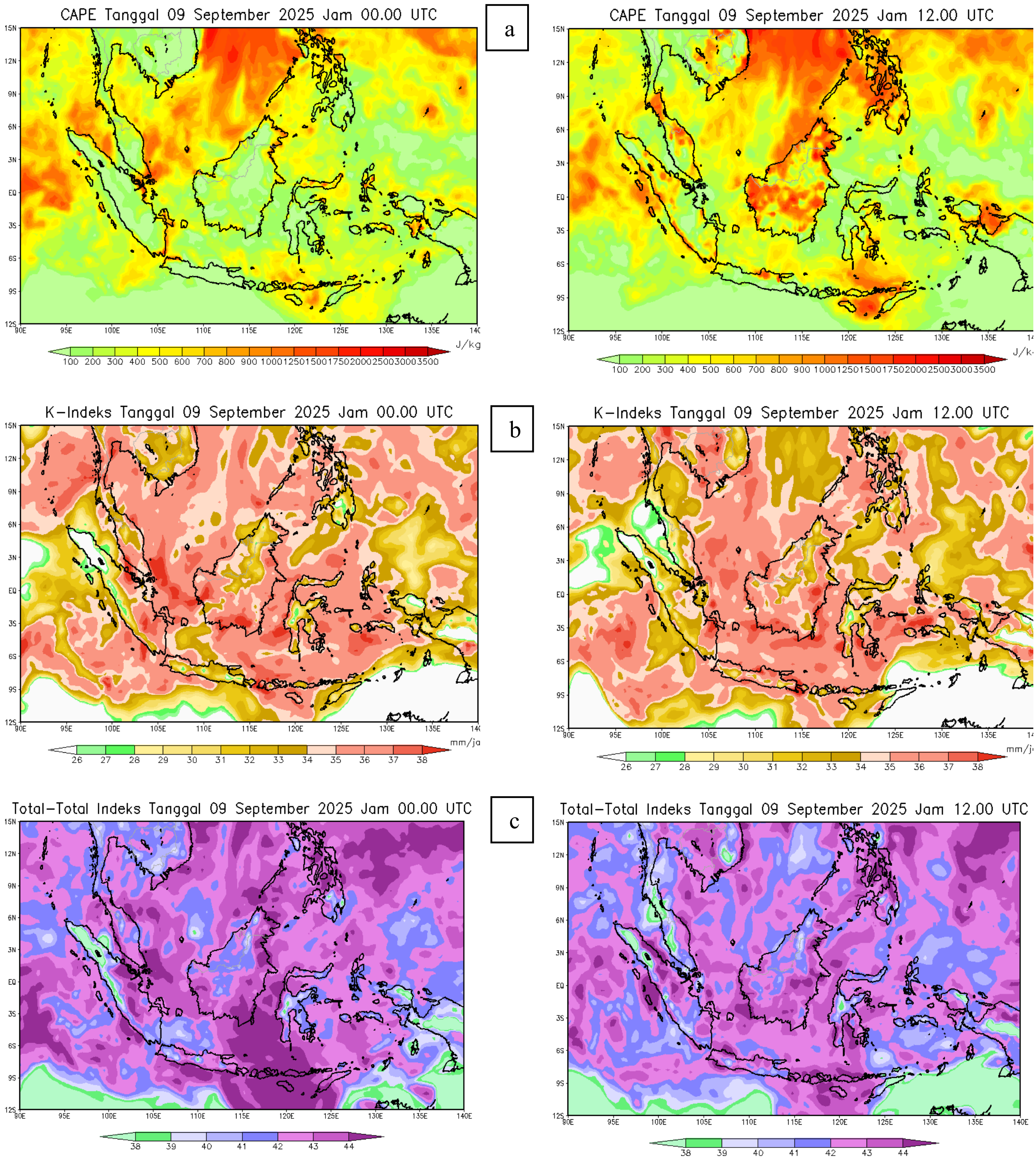

Fig. 13 Spatial distribution of atmospheric instability indices over Bali on 9 September 2025 at 00.00 UTC and 12.00 UTC: (a) Convective Available Potential Energy (CAPE), (b) K-Index, and (c) Total Totals Index

3.4. Multiscale Interaction and Implications

By integrating all scales, it becomes clear that the extreme rainfall event on 9 September 2025 resulted from a coupled multiscale process, which is consistently reflected in the observed rainfall distribution.

At the global level, neutral ENSO and IOD conditions indicate that interannual forcing was minimal. However, the active MJO provided strong intraseasonal forcing, enhancing large-scale convection and promoting widespread atmospheric ascent over the Maritime Continent.

At the regional level, positive SST anomalies, low-level convergence, and strong moisture transport created a favorable dynamical environment for sustained upward motion. These conditions ensured a continuous supply of moisture and energy to the system, which is essential for maintaining convective processes over a prolonged period.

At the local level, this accumulated energy was released in the form of deep convective clouds, as identified from Himawari-8 observations, despite relatively weak thermodynamic instability. The dominance of dynamic forcing allowed convection to develop efficiently even under marginal instability conditions.

The impact of this multiscale interaction is clearly reflected in the rainfall observations. As shown in Fig. 14, several areas in Bali experienced daily rainfall exceeding 100 mm/day, which falls into the extreme rainfall category. The spatial distribution of rainfall indicates that regions affected by strong moisture convergence and persistent convective activity correspond well with areas of highest rainfall intensity.

This agreement between atmospheric conditions and observed rainfall confirms that the interaction between large-scale (MJO), regional (moisture transport and convergence), and local (convective processes) mechanisms directly controlled the intensity and distribution of the extreme rainfall event. Therefore, this study highlights that multiscale coupling is a key mechanism in extreme rainfall events over the Maritime Continent, where the linkage between atmospheric dynamics and observed precipitation becomes essential for understanding and predicting high-impact weather events.

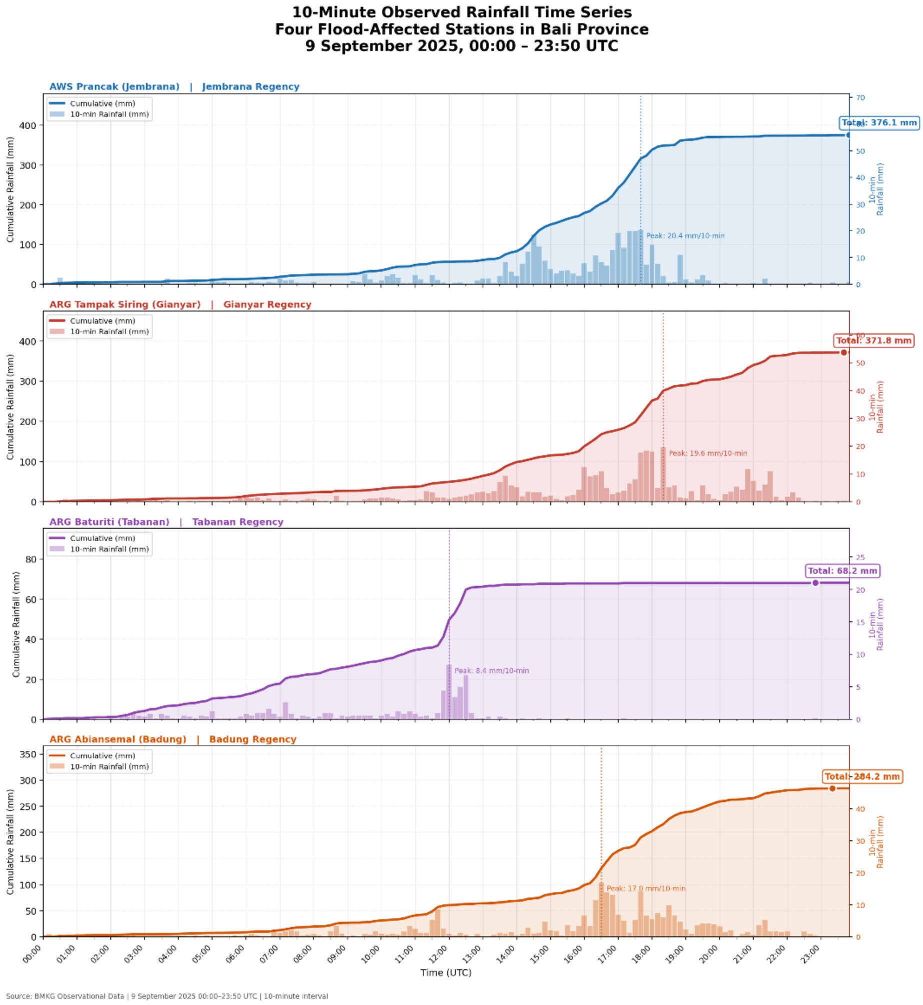

Fig. 14 Spatial distribution of daily rainfall over Bali on 9 September 2025

4. CONCLUSION

This study demonstrates that the extreme rainfall event in Bali on 9 September 2025 was primarily driven by the interaction of atmospheric processes across multiple scales. At the global scale, ENSO and IOD were in neutral conditions, indicating a limited influence from interannual variability. However, the presence of an active Madden–Julian Oscillation (MJO) played a significant role in enhancing large-scale convection over the Maritime Continent.

At the regional scale, favorable conditions such as positive sea surface temperature anomalies, low-level moisture convergence, and enhanced moisture transport contributed to the development of upward motion and sustained convective activity. At the local scale, deep convective clouds were observed, although atmospheric instability was relatively weak, suggesting that dynamic forcing was more dominant than thermodynamic factors in triggering the extreme rainfall.

These findings highlight the importance of multiscale interactions in controlling extreme rainfall events in tropical regions. In particular, strong intraseasonal variability such as the MJO, combined with regional atmospheric dynamics, can produce extreme rainfall even under marginal instability conditions.

From a practical perspective, this study suggests that early warning systems in Indonesia should not rely solely on traditional indicators such as local instability indices, but also incorporate large-scale and intraseasonal signals, especially MJO activity. Integrating these factors into operational forecasting could improve the accuracy of extreme weather predictions and support more effective disaster risk reduction strategies.

REFERENCE

[1] E. Aldrian and R. D. Susanto, “Identification of three dominant rainfall regions within Indonesia and their relationship to sea surface temperature,” *Int. J. Climatol.*, vol. 23, no. 12, pp. 1435–1452, 2003, doi: 10.1002/joc.950.

[2] S. Supari, F. Tangang, E. Salimun, E. Aldrian, A. Sopaheluwakan, and L. Juneng, “ENSO modulation of seasonal rainfall and extremes in Indonesia,” *Clim. Dyn.*, vol. 51, pp. 255–271, 2018, doi: 10.1007/s00382-017-3939-5.

[3] A. R. As-syakur, T. Tanaka, T. Osawa, and M. S. Mahendra, “Indonesian rainfall variability observation using TRMM data: The impacts of ENSO and IOD,” *Int. J. Climatol.*, vol. 34, no. 5, pp. 1568–1579, 2014, doi: 10.1002/joc.3799.

[4] M. C. Wheeler and H. H. Hendon, “An all-season real-time multivariate MJO index: Development of an index for monitoring and prediction,” *Mon. Weather Rev.*, vol. 132, no. 8, pp. 1917–1932, 2004, doi: 10.1175/1520-0493(2004)132<1917:AARMMI>2.0.CO;2.

[5] S. C. Peatman, J. Schwendike, and C. E. Birch, “A local-to-large scale view of Maritime Continent rainfall: Control by ENSO, MJO, and equatorial waves,” *J. Climate*, vol. 34, no. 22, pp. 1–20, 2021. [Online]. Available: https://journals.ametsoc.org/view/journals/clim/34/22/JCLI-D-21-0263.1.xml

[6] C. P. Chang, Z. Wang, J. McBride, and C. H. Liu, “Annual cycle of Southeast Asia–Maritime Continent rainfall and the asymmetric monsoon transition,” *J. Climate*, vol. 17, no. 11, pp. 2205–2223, 2004, doi: 10.1175/1520-0442(2004)017<2205:ACOSAM>2.0.CO;2.

[7] S. W. Lubis, S. Hagos, and E. Hermawan, “Record-breaking precipitation in Indonesia’s capital of Jakarta in early January 2020 linked to the Madden–Julian Oscillation,” *Geophys. Res. Lett.*, vol. 49, no. 24, 2022, doi: 10.1029/2022GL101513.

[8] M. Mughozali et al., “Analysis of cloud-top temperature for identification of convective clouds using Himawari-8 satellite data,” *J. Remote Sens.*, 2017.

[9] COMET Program, “Convective instability indices (CAPE, K-Index, Total Totals),” UCAR MetEd, 2013. [Online]. Available: https://www.meted.ucar.edu

[10] P. Chen et al., “Monsoonal extreme rainfall in Southeast Asia: A review,” *Water*, vol. 17, no. 1, 2024. [Online]. Available: https://www.mdpi.com/2073-4441/17/1/5

[11] D. Satiadi, A. Purwaningsih, and W. Harjupa, “Impacts of MJO phenomena on diurnal cycle of local convection, moisture convergence, and rainfall,” *Meteorol. Atmos. Phys.*, 2023, doi: 10.1007/s00703-023-00979-w.

[12] M. N. Islam, H. Uyeda, and T. Terao, “Diurnal variations of cloud activity and rainfall in the tropical region,” *Atmos. Res.*, vol. 209, pp. 1–13, 2018, doi: 10.1016/j.atmosres.2018.03.010.

[13] J. Y. Lee, “Seasonal prediction and variability of the Maritime Continent climate,” *Clim. Dyn.*, vol. 45, pp. 1–15, 2015, doi: 10.1007/s00382-015-2671-7.

[14] X. Li, R. Lu, G. Chen, and R. Chen, “Western North Pacific tropical cyclones suppress Maritime Continent rainfall,” *npj Clim. Atmos. Sci.*, 2024, doi: 10.1038/s41612-024-00810-2.

[15] D. S. Permana et al., “The role of tropical waves in the genesis of extreme weather over the Maritime Continent,” *Nat. Commun.*, 2023, doi: 10.1038/s41467-023-36498-w.

[16] Risyanto et al., “Southerly surge impact on rainfall patterns in Southern Indonesia during MJO events,” *Atmosphere*, vol. 15, no. 7, 2024. [Online]. Available: https://www.mdpi.com/2073-4433/15/7/840

[17] Ferrett, S., Methven, J., and Woolnough, S. J., “Hybrid dynamical–statistical forecasts of rainfall risk in Southeast Asia dependent on equatorial waves,” *Mon. Weather Rev.*, 2023.