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Spatiotemporal Evolution of Mesoscale Convective Systems (MCSs) and Rainfall Over Citarum River Basin, West Java

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ABSTRACT

Mesoscale convective systems (MCSs) are major contributors to extreme rainfall in tropical regions, yet their lifecycle-dependent rainfall characteristics over the Indonesian Maritime Continent remain poorly documented. This study investigates the spatiotemporal evolution of MCSs and associated rainfall over the Citarum River Basin, West Java. We focused on the rainy seasons of 2013–2023, based on hourly infrared satellite data and IMERG precipitation. The results reveal a pronounced diurnal cycle, and up to 70% MCS events occurred at the afternoon–night period (12–24 LT). MCSs generally start over upstream mountainous areas and propagate toward the central and downstream basin at night, indicating a strong topographic influence. Our findings show that the mature phase of MCS produces the highest intensity and frequency of heavy rainfall (>10 mm h^{-1}), whereas the dissipation phase contributes to persistent stratiform rainfall. Further, we find that most extreme rainfall in the basin is triggered by MCSs. These findings highlight the role of MCS evolution and basin topography in shaping extreme rainfall characteristics and may support improvements in extreme weather monitoring and early warning systems.

KEYWORDS

diurnal cycle, extreme rainfall, hydrometeorological hazards, topographic forcing, temporal evolution

1. INTRODUCTION

Extreme weather events associated with organized convective systems remain difficult to predict and continue to challenge forecasting systems. These events can produce severe socio-economic impacts, particularly in densely populated tropical regions (Atiah et al., 2023; Feng et al., 2024). Previous studies have shown that mesoscale convective systems (MCS), defined as organized clusters of deep con-vection, are frequently associated with extreme rainfall and other high-impact weather phenomena (Chen et al., 2021). Therefore, understanding the development and evolution of MCS is important for improving rainfall forecasting and enhancing hydrometeoro-logical early warning capabilities.

MCS is formed through the aggregation and evolution of cumulonimbus clouds into large-scale systems that can extend over hundreds of kilometers (Houze, 2018; Schumacher and Rasmussen, 2020). The systems are capable of producing high-intensity, long-duration precipitation (Hu et al., 2021). Repeated occur-rences of MCS over the same region can increase the potential for flood hazards, particularly in densely populated downstream areas (Houze, 2018; Hu et al., 2021).

Advances in satellite remote sensing improve monitoring the formation, evolution, and propagation of MCS (Kolios and Feidas, 2010). However, researches on this topic over the Indonesian Maritime Continent are limited, particularly over basin scale. How different phases of the MCS lifecycle influence rainfall intensity and spatial distribution within tropical river basins still poorly understood. Better understanding this will improve water related disaster management and preparedness in the region relates to persistence of heavy rainfall events due to MCS.

Flood is one of the most frequent hydrometeorological hazards in Indonesia, and it frequently occurs as well in the Citarum River Basin, West Java. Most MCS studies in Indonesia focused on the climatology and physical structure of convective systems (Nuryanto et al., 2018, 2017; Putri et al., 2018; Trismidianto, 2018; Trismidianto et al., 2017), but MCS lifecycle evolution and its contribution to basin-scale rainfall are poorly investigated.

This study investigates the spatiotemporal characteristics of MCS over West Java and examines how different phases of the MCS lifecycle influence rainfall intensity in the Citarum River Basin. By combining satellite-based MCS tracking with precipitation observations, this study provides new insights into lifecycle-dependent rainfall characteristics in a tropical watershed. These findings contribute to improving the understanding of lifecycle-dependent rainfall variability associated with MCS and provide useful insights for future studies on heavy rainfall and related hydrometeorological hazards.

2. MATERIALS AND METHODS

2.1 Study Area and Data

This study was carried out in the Citarum River Basin, West Java, which is geographically located at 5.9°S–6.8°S and 107.0°E–107.6°E. The Basin has an area of 6,614 km², with diverse topographic conditions, ranging from mountainous regions in the southern part to lowland areas in the northern part, which border the northern coast of Java (Figure 1). Several major sub-basins within the Citarum Basin include the Cisangkuy, Cikapundung, Citarik, Cibeet, and Ciherang watersheds, all of which drain into the Citarum River, flowing northward toward the Java Sea.

This study used the infrared brightness temperature (TBB) data to track MCS (Table 1). The data were obtained from the NASA Global Merged IR V1 product, which integrates observations from multiple geostationary satellites (Janowiak et al. 2017). The dataset has a spatial resolution of 4 km and a temporal resolution of 1 hour, consistent with established approaches for MCS tracking (Feng et al., 2021).

Precipitation Feature (PF) data from the GPM IMERG V06B product are utilized. This dataset is a passive microwave (PMW) based precipitation product that leverages water vapor motion vectors (Tan et al., 2019). IMERG data are originally provided at a temporal resolution of 30 minutes and a spatial resolution of 0.1°, then it was averaged into hourly intervals to optimize computational efficiency while maintaining analytical precision for MCS dynamics (Feng et al., 2021).

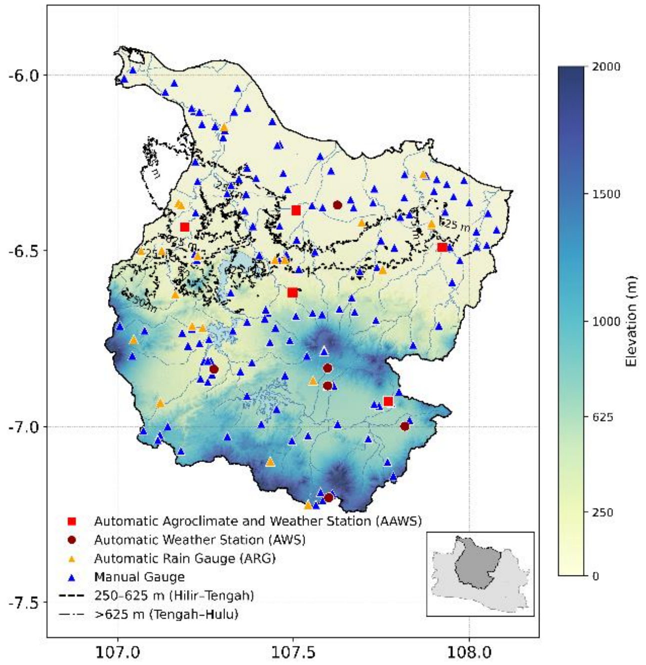

Figure 1. Distribution of rainfall monitoring stations over Citarum River Basin in West Java, at various elevation gradients.

We validated IMERG satellite data using daily precipitation observations from manual rain gauge stations operated by the Indonesian Bureau of Meteorology, Climatology, and Geophysics (BMKG). In addition, hourly rainfall observations from 29 Automatic Rain Gauges (ARG), 5 Automatic Weather Systems (AWS), and 4 Automatic Agroclimate and Weather Systems (AAWS) were used to evaluate rainfall characteristics associated with different phases of the MCS lifecycle within the Citarum Basin.

Tabel 1. Summary of observational and reanalysis datasets used in this study (Domain: 5°–8°S,105°–108°E).

Data	Res	Period
NASA Global Merged IR V1 (TBB), Hourly	0.04°	2013 – 2023
GPM IMERG V06B, Hourly	0.1°	2013 – 2023
BMKG Manual Rain Gauge, Daily		2013 – 2023
BMKG Automatic Rain Gauge, Hourly		2019 – 2023
ERA5 wind 925 hPa (u10, v10), Hourly	0.25°	2013 – 2023
ERA5 temperature 2m (T2m), Hourly	0.25°	2013 – 2023

2.2 Methods

The methodological framework for identifying, tracking, and analyzing Mesoscale Convective Systems

(MCS) and their associated rainfall characteristics is illustrated in Figure A1. Cold Cloud Systems (CCS)—defined as contiguous regions of low infrared brightness temperature (T_{BB}) representing deep convective cloud tops—serve as the core tracking objects. Combining satellite T_{BB} and IMERG precipitation data, the PyFLEXTRKR algorithm was applied through three primary processing steps (Feng et al., 2021, 2019, 2018), as follow:

1. MCS Identification and Tracking

   Convective cloud systems were identified using cold cloud cores ($T_{BB} \leq -52$°C) and cloud shields ($T_{BB} \leq -32$°C). Systems were tracked across consecutive time steps using a 50% spatial overlap criterion. An organized convective system was classified as an MCS if it maintained an area ≥ 2.000 km^2 a duration ≥ 3 hours and a Precipitation Feature (PF) intensity ≥ 2 mm h^{-1} (Nuryanto et al., 2021). Based on PF eccentricity (ϵ), MCS events were further categorized into Deep Circular Convective Systems (DCCS, $\epsilon \geq 0.7$) and Deep Elongated Convective Systems (DECS, $0.2 \leq \epsilon < 0.7$).

2. Linking MCS with Daily Rainfall

   The spatial relationship between MCS occurrence and heavy daily rainfall (≥ 50 mm day^{-1} was evaluated within a 100 km radius using two spatial domains: the MCS center (minimum $T_{BB} \leq -52$°C) and the anvil region (cloud shield T_{BB} between -52°C and -32°C with PF intensity > 10 mm h^{-1}) (Ding et al., 2023; Feng et al., 2019). To align with the BMKG daily rainfall observation window (recorded at 07:00 local time on day H), rainfall data from both the preceding day (H−1) and the observation day (H) were evaluated.

3. MCS Lifecycle Classification

   Each MCS was tracked across three evolutionary stages: genesis, mature, and dissipation. Automatic rain gauge (ARG) stations within 100 km of the MCS center and anvil region were used to link these lifecycle phases with surface rainfall. The temporal lag was calculated as the time difference between the occurrence of a given MCS phase and the peak hourly rainfall intensity, where positive values indicate rainfall succeeding the MCS phase and negative values indicate rainfall preceding it.

3. RESULTS AND DISCUSSION

3.1 Spatial Distribution and Diurnal Variation of MCS

A total of 340 MCS systems were identified over West Java during the DJF season for the period 2013–2023. 87 systems were found to affect the Citarum Basin, defined as MCS whose cloud-system centroids intersected the Citarum Basin at any stage of their lifetime during their lifetime (Table A1). Because MCS lifetimes commonly span several hours, individual systems may contribute to more than one 6-hour interval in the diurnal analysis. Therefore, the summed frequencies across intervals exceed the total number of identified MCS events.

Within the basin, MCS activity exhibits a pronounced diurnal cycle, with the lowest occurrence during 06–12 LT (9.0%) and peak activity during the afternoon and evening, particularly 12–18 LT (34.4%) and 18–24 LT (35.2%). During 12–18 LT, MCS are primarily concentrated over the upstream mountainous region, with a mean CCS area of about 98,070 km² and an average duration of 16.1 hours, indicating frequent convective initiation over elevated terrain. Activity subsequently shifts toward the central basin during 18–24 LT, when systems reach their largest average size (129.576 km²) and longest duration (16.8 hours), consistent with the mature stage of organized convection. During 00–06 LT (21.3%), MCS activity becomes more prevalent in the downstream lowlands, suggesting continued propagation toward the northern basin before gradual weakening. These patterns indicate a coherent upstream-to-downstream migration of MCS activity across the Citarum Basin (Figure 2).

The observed diurnal migration suggests a close linkage between MCS activity and the evolution of lower-tropospheric atmospheric conditions over the region.

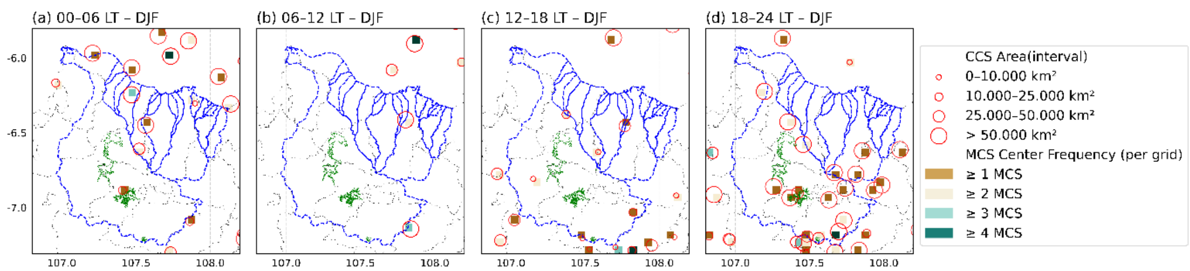

Figure 2. Diurnal variation and spatial distribution of MCS centers during DJF at four 6-hour intervals: (a) 00–06 LT, (b) 06–12 LT, (c) 12–18 LT, and (d) 18–24 LT. Circle size denotes CCS area, and grid shading represents the frequency of MCS center occurrence per grid cell.

To further investigate the mechanisms control-ling the development and propagation of MCS, the spatial patterns of 925-hPa winds, 2-m air temperature, and meridional convergence during the DJF season were subsequently analyzed (Figure A2). Composite 925-hPa wind and 2-m air temperature fields indicate enhanced surface heating from midday to late after-noon, particularly over the upstream and central parts of the Citarum Basin. This heating is followed by the development of a land–sea thermal gradient. Such conditions promote the strengthening of local circu-lation and low-level wind convergence during 12–18 LT, coinciding with the increased occurrence of MCS in their early growth phase (Houze Jr., 2004; Wallace and Hobbs, 2006). During 18–24 LT, the convergence intensifies and expands spatially from the upstream–central region toward the central–downstream areas, accompanied by surface cooling and the development of offshore (land-to-sea) flow.

The Hovmöller diagram (Figure A2) illustrates the meridional migration of maximum convergence from southern to northern latitudes throughout the diurnal cycle. This pattern is consistent with the spatial shift of MCS activity from the upstream region during the afternoon toward the central and downstream areas at night, a behavior commonly observed in tropical conti-nental convective systems. These results suggest that topographic forcing, diurnal surface heating, and land–sea interactions collectively regulate the initiation, organization, and nocturnal propagation of MCS across the Citarum Basin.

3.2 Spatial Association of MCS Centers and Anvil Regions with Daily Rainfall

The spatial distribution of heavy rainfall over the Citarum Basin reveals a distinct dependency on the evolutionary stage of Mesoscale Convective Systems (MCSs), spanning from their initial development phase (H−1) to their peak mature state (H) relative to daily rainfall accumulations.

Using the MCS center approach, heavy rainfall frequency during the initial stage (H−1; Figure A3) is low and spatially scattered (≤ 7 events per grid cell). As the system progresses to its peak state on day H, rainfall frequency increases substantially to appro-ximately 20 events per grid cell, becoming strongly concentrated over the central to upstream regions of the basin. In contrast, the anvil-based approach exhibits broader spatial coverage and consistently high rainfall frequency across both early (H−1) and peak stages (H), with precipitation impacts extending toward the central and downstream areas.

These spatial patterns reveal distinct physical mechanisms driving precipitation across the basin. The sharp increase in rainfall frequency at the MCS center on day H indicates that intense, localized downpours are directly tied to active convective cores (Rickenbach et al., 2008). Conversely, the widespread rainfall distri-bution under the anvil region highlights the role of persistent, large-scale precipitation generated du-ring the mature stratiform stage (Yuan and Houze 2010b). The transition from H−1 to H demonstrates that heavy rainfall in the Citarum Basin is governed not only by the presence of active convective cores, but also by the temporal persistence of MCSs and their interactions with regional topography (Rickenbach et al., 2008; Wall et al., 2018).

Overall, MCSs contribute approximately 45% of the total rainfall in the Citarum Basin, whereas the remaining 55% originates from non-MCS mechanisms such as localized convection, orographic lifting, and un-organized convective processes (Wu et al., 2023). This dual spatial impact poses significant hydrometeo-rological risks: active convective cores over upstream regions elevate the risk of flash floods and rapid runoff, while persistent anvil-driven rain downstream increases vulnerability to prolonged riverine flooding across the lower basin.

Table 2. Lifecycle-dependent characteristics of rainfall associated with MCS event.

MCS Phase	Number of Events	HeavyRain (hours)	Absolute Maximum Rainfall (mm h⁻¹)	Heavy Rainfall Frequency (%)	Maximum Hourly Rainfall (P95, mm h⁻¹)
Genesis	46	14	32.8	30.4	7.3
Mature	46	17	46.2	37.0	37.8
Dissipation	45	4	46.2	8.9	29.8

3.3 Spatial Distribution of Maximum Hourly Rainfall Based on MCS Phases

The spatial distribution of maximum hourly rainfall associated with different phases of the MCS lifecycle is presented in Figure A4. During the genesis phase, rainfall intensity is generally weak and spatially localized, with most events classified within the light to moderate rainfall categories (0.5–10 mm h^{-1}). This pattern reflects the early stage of convective development, when convective cells remain relatively isolated and have not yet evolved into fully organized MCS structures.

Rainfall intensity increases substantially during the mature phase, as heavy rainfall events (>10 mm h^{-1}) become more frequent and spatially widespread across the central and upper parts of the Citarum Basin. This phase corresponds to the period of strongest convective organization and peak rainfall intensity within the MCS lifecycle.

The statistical characteristics summarized in Table 2 support the spatial patterns shown in Figure A4. Both heavy rainfall frequency and extreme rainfall intensity (P95) reach their highest values during the mature phase, indicating that this stage plays an important role in generating intense precipitation over the basin.

As the system transitions into the dissipation phase (Figure A4), the frequency of heavy rainfall decreases and rainfall intensity generally weakens compared to the mature phase. Nevertheless, localized intense rainfall may still occur, as indicated by the comparable absolute maximum rainfall observed during the mature and dissipation phases (46.2 mm h^{-1}). This behavior suggests that rainfall during the late stage of MCS evolution remains influenced by residual convective activity embedded within broader stratiform precipitation regions (Wall et al., 2018; Zheng et al., 2013).

The temporal evolution further demonstrates that both heavy rainfall frequency and extreme rainfall intensity increase markedly from the genesis to mature phase before gradually weakening during dissipation. Although rainfall intensity decreases during the later stage, precipitation may persist for several hours due to continued stratiform rainfall contributions (Wall et al., 2018). Such persistence may prolong rainfall duration over the watershed and enhance runoff accumulation, thereby increasing flood potential within the Citarum Basin.

This study highlights several basin-specific characteristics of MCS-related rainfall over the Citarum Basin. The spatial distribution of MCS-related rainfall suggests the influence of basin topography on convective evolution. In particular, the mature phase is associated with the highest rainfall intensity and heavy rainfall frequency, indicating its important role in extreme rainfall generation. Meanwhile, the persistence of rainfall during the dissipation phase suggests that stratiform precipitation may prolong hydrological impacts beyond the peak convective stage. Overall, these findings demonstrate that the interaction between MCS lifecycle evolution and basin characteristics plays an important role in shaping rainfall variability over the Citarum Basin.

4. CONCLUSION

This study investigated the spatiotemporal characteristics of mesoscale convective systems (MCSs) and their associated rainfall over the Citarum River Basin during the DJF season from 2013 to 2023. The results reveal a pronounced diurnal cycle in which convective initiation frequently develops over the upstream mountainous regions during the afternoon and subsequently propagates toward the central and downstream basin during nighttime hours. This migration pattern is likely influenced by local circulation and topographic effects.

Rainfall characteristics show a clear dependence on the MCS lifecycle. The mature phase is associated with the highest rainfall intensity and the greatest frequency of heavy rainfall events, indicating its important role in producing extreme precipitation over the basin. In contrast, the dissipation phase is characterized by weaker but more persistent rainfall, suggesting continued contributions from stratiform precipitation that may prolong rainfall duration and enhance cumulative runoff potential.

This study further demonstrates a spatial relationship between MCS evolution and basin-scale rainfall distribution over the Citarum Basin. The transition from intense convective rainfall in the upstream region during the mature phase to more persistent rainfall in downstream areas during dissipation suggests a downstream extension of rainfall impacts associated with MCS evolution. Although MCSs contribute approximately 45% of total rainfall, they are strongly associated with extreme rainfall events that may contribute to flood occurrence within the basin

Overall, these findings provide important insights into the relationship between MCS lifecycle evolution and rainfall variability over the Citarum Basin. The identified temporal and spatial characteristics of MCS-related rainfall may support hydrometeorological risk assessment and early warning efforts in the region. Future studies integrating hydrological variables, such as river discharge, soil moisture, and basin storage conditions, are recommended to further evaluate the linkage between MCS evolution and basin-scale flood responses.

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ANNEX

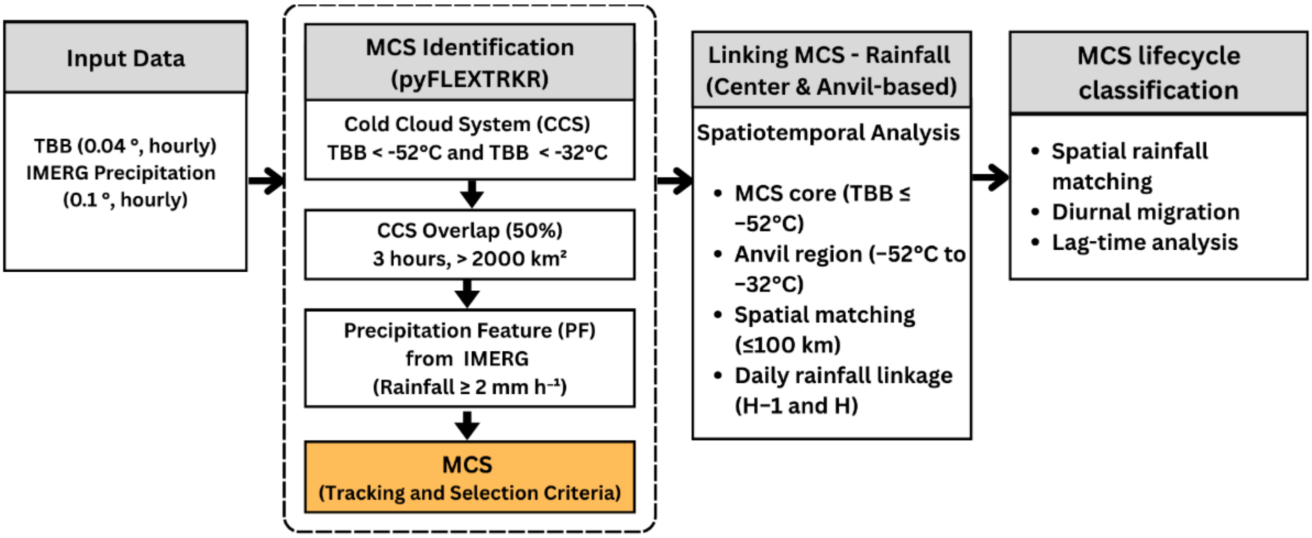

Figure A1. Workflow of MCS detection, tracking, and rainfall association analysis.

Table A1. Diurnal Characteristics of MCS Affecting the Citarum Basin During DJF (2013–2023).

Time Interval (LT)	Number of MCS	Mean CCS Area (km^2)	Occurrence Percentage (%)	Mean MCS Duration (hours)	Location
00 – 06	26	84.911	21.3	14.5	Downstream
06 – 12	11	140.045	9	12.9	Downstream
12 – 18	42	98.070	34.4	16.1	Downstream
18 - 24	43	129.576	35.2	16.8	Upstream

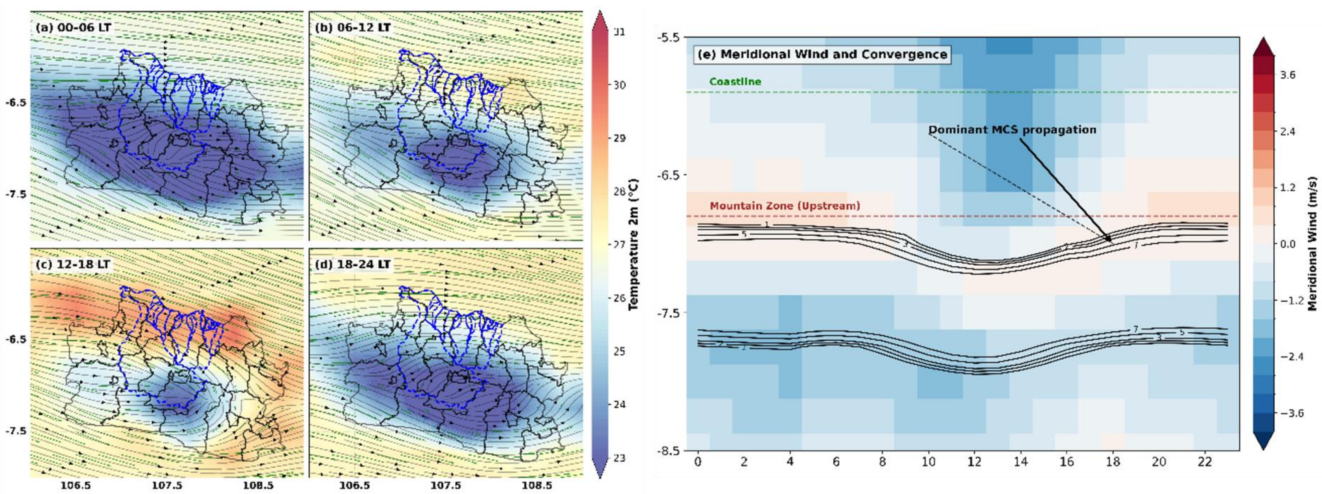

Figure A2. Diurnal evolution of 925-hPa wind vectors and 2-m air temperature, and € meridional wind convergence during DJF (2013–2023) over the Citarum Basin.

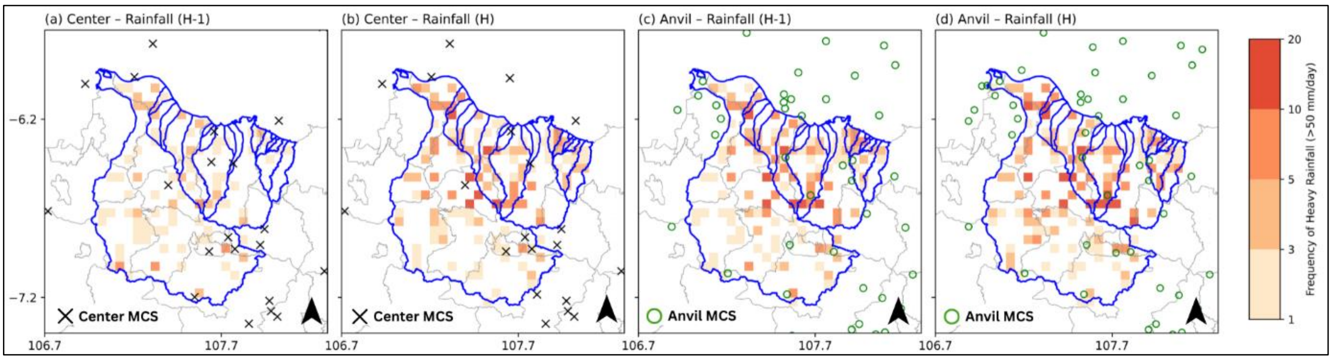

Figure A3. (a) and (c) Spatial distribution of MCS centers and anvil regions associated with daily rainfall frequency on the day prior to rainfall observation (H−1); (b) and (d) spatial distribution of MCS centers and anvil regions associated with daily rainfall frequency on the rainfall observation day (H).

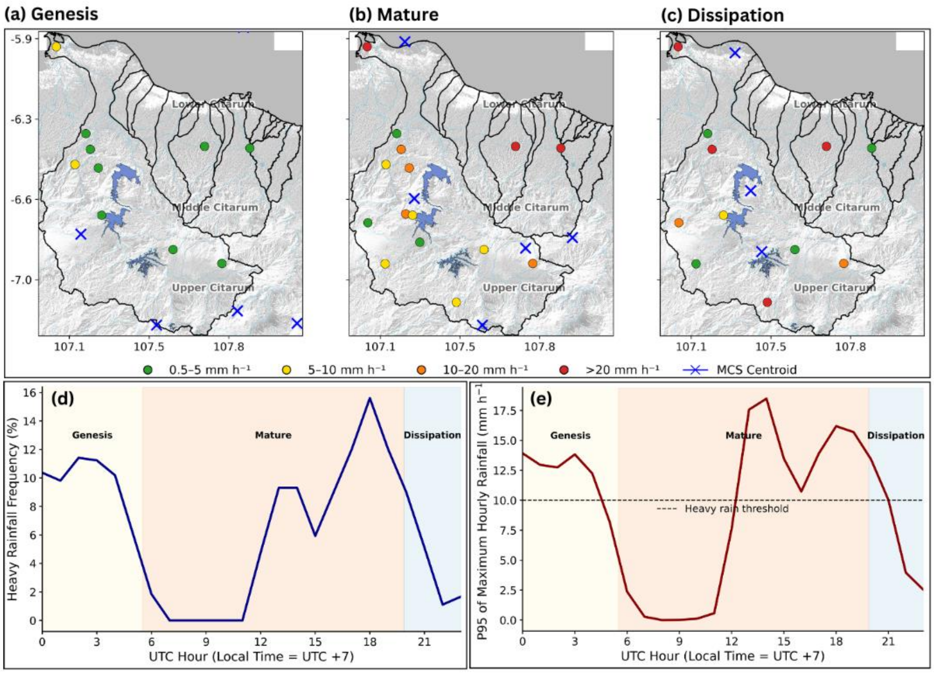

Figure A4. Spatial distribution and temporal evolution of maximum hourly rainfall associated with MCS lifecycle phases over the Citarum Basin during DJF. Panels (a–c) show rainfall distribution during the genesis, mature, and dissipation phases, while panels (d–e) present the temporal variation of heavy rainfall frequency and P95 of maximum hourly rainfall. Colored circles indicate rainfall intensity classes and blue crosses denote MCS centroids.