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Identification of Mesoscale Convective System Phenomena in Relation to Heavy Rain in Semarang (Case Study of the Squall Line on March 13, 2024)

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ABSTRACT

Indonesia, located in the equatorial region, experiences complex rainfall variability influenced by various climatic and geographic factors. Mesoscale Convective Systems (MCS), including squall lines, are a significant contributor to extreme weather phenomena such as heavy rainfall and strong winds. This study investigates the mesoscale convective system (MCS) phenomenon, focusing on its formation, atmospheric dynamics, and associated rainfall distribution.

This research investigates the squall line phenomenon, specifically focusing on a squall line event in Semarang, Indonesia, on March 13, 2024. Utilizing data from Himawari-8 satellite imagery, ERA5 reanalysis, and GSMaP rainfall observations, the research identifies the development, atmospheric dynamics, and rainfall intensity of the squall line. Satellite imagery analysis revealed the squall line's linear pattern with cloud top temperatures below -60°C, forming during intense convective activity. Atmospheric instability indices, including CAPE and LI, indicated favorable conditions for squall line development, based on a Skew-T Log-P diagram, shows CAPE values reaching 427 J/kg, minimal CIN, and increasing wind shear with altitude. Rainfall distribution analysis identified localized extreme precipitation exceeding 120 mm within the study period, which aligns with the squall line's trajectory. The findings highlight the significant role of squall lines in triggering heavy rainfall and hydrometeorological disasters in Indonesia, emphasizing the need for accurate monitoring and early warning systems.

The findings highlight the critical role of mesoscale dynamics in triggering squall lines and their potential to induce hydrometeorological disasters. This study underscores the need for improved monitoring and forecasting of MCS events to mitigate their impacts on vulnerable regions like Semarang.

Keywords : mesoscale convective system; squall line; Semarang; extreme rainfall; satellite imagery

I. INTRODUCTION

Indonesia, a tropical archipelago located along the equatorial region, is renowned for its abundant rainfall and diverse climatic phenomena. Its unique geographical position and varied topographical features contribute to complex rainfall patterns influenced by multiple atmospheric and oceanic factors such as latitude, altitude, wind systems, and regional climatic interactions [1][2]. Rainfall in Indonesia is characterized by significant variability, shaped by both local and large-scale drivers, which makes the region particularly susceptible to extreme weather events. One prominent weather phenomenon responsible for extreme rainfall in Indonesia is the Mesoscale Convective System (MCS).

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The Mesoscale Convective System (MCS) is a large, organized cluster of thunderstorms accompanied by sustained precipitation areas, often extending over several hundred kilometers [3]. MCS encompasses various convective systems, including the Squall Line, which is distinguished by its linear organization and potential for producing severe weather [4]. As identified by Maddox (1980) [5], MCS systems, especially squall lines, are notable for their capacity to generate heavy rainfall, strong winds, and localized severe weather events with substantial societal and environmental impacts. Squall lines are characterized by their linear structure exceeding 250 km in length, often developing in tropical regions like Indonesia, where they are fueled by abundant moisture, atmospheric instability, and favorable wind dynamics [6][7].

Squall lines, as a subset of MCS, are particularly significant due to their role in triggering extreme weather events. According to Houze (1997) [9], a squall line consists of a leading edge of intense convective precipitation, often accompanied by severe weather, followed by a broader stratiform precipitation region. These systems are associated with rapid movement and organized linear convection, often driven by atmospheric processes such as wind shear and moisture convergence. Bluestein and Jain (1985) [11] classified squall lines into four formation types: broken line, back-building, solid line, and broken area, highlighting the diversity of their development mechanisms and impacts.

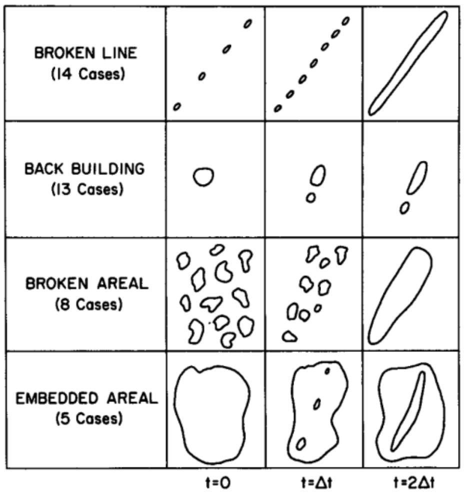


Fig. 1. Ideal shapes of Squall Line

The climatic context of Indonesia further accentuates the relevance of squall lines. The country's rainfall patterns are heavily influenced by seasonal drivers such as the Asian-Australian Monsoon, intra-seasonal oscillations like the Madden-Julian Oscillation (MJO), and inter-annual phenomena such as the El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) [12][13][14]. These climatic forces modulate the atmospheric conditions conducive to MCS formation, leading to extreme weather anomalies during specific periods. For instance, moisture-laden conditions during favorable MJO phases or La Niña episodes can enhance the likelihood of squall line development, increasing the risk of hydrometeorological disasters such as flash floods and damaging winds [15][16].

Recent studies on squall lines in Indonesia underscore their significant impact and unique characteristics. Hidayat et al. (2019) observed that squall lines in Indonesia often exhibit elongated convective structures lasting over six hours, with cloud tops exceeding 17 km and extremely low temperatures below -45°C. These systems, particularly those forming over land, tend to produce more intense rainfall (up to 50.1 mm/hour) compared to maritime-based squall lines [17]. Similarly, Tirtanegara et al. (2019) documented squall lines in West Kalimantan, noting their formation in a broken line pattern with a length of approximately 300 km, a lifespan of nearly six hours, and peak reflectivity of 51.5 dBZ, alongside wind speeds reaching 27 m/s [18].

In regions like Semarang, where the monsoonal climate and urban landscape amplify vulnerability, understanding squall line behavior is critical. The interplay between local topography, atmospheric dynamics, and regional climatic anomalies often sets the stage for squall lines to produce extreme rainfall and associated hazards. By studying the development, structure, and impacts of squall lines, this research aims to enhance predictive capabilities and provide actionable insights for mitigating the risks associated with these high-impact weather systems.

II. METHOD

This research was conducted in the Semarang region, with a geographic focus on coordinates approximately 6°S - 8°S and 109°E - 111°E on the geographic map of Semarang to visualize the distribution of mesoscale convective systems, including phenomena such as squall lines.

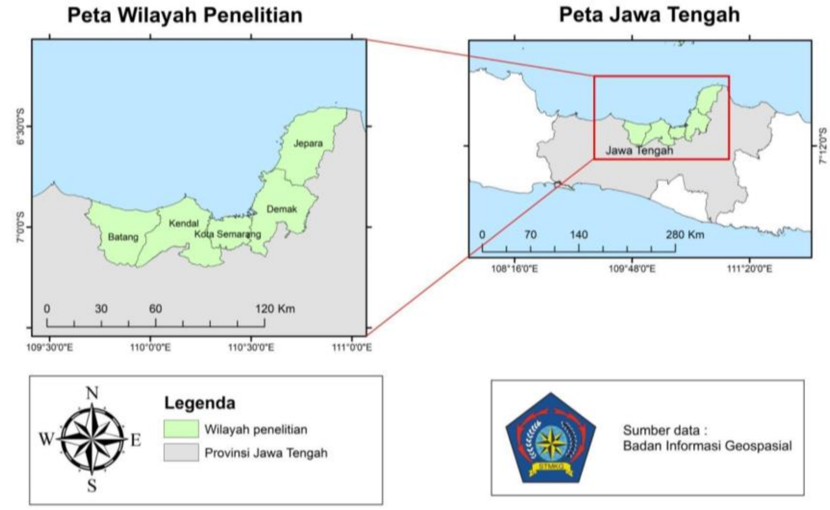


Fig. 2. Semarang City map

The data utilized in this research comprises three main components: satellite imagery, reanalysis wind data, and rainfall observation data, each serving a specific purpose in supporting the analysis. To begin with, satellite imagery was acquired from the Himawari-8 satellite using the FileZilla application. Specifically, Band-13 Infrared (IR) data was selected due to its effectiveness in identifying cloud top temperatures, which are critical for monitoring convective cloud development. The imagery features a high temporal resolution of 10 minutes and was captured on March 13, 2024, between 01:30 and 07:30 UTC, allowing for detailed observation of atmospheric changes over time.

In addition, reanalysis wind data were sourced from the ERA5 dataset provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). These data were employed to examine the upper-air atmospheric profile, with a particular focus on assessing atmospheric instability. The analysis aimed to understand the potential for convective cloud formation by utilizing relevant instability indices derived from the dataset.

Furthermore, rainfall observation data were obtained from the Global Satellite Mapping of Precipitation (GSMaP) product. This dataset offers a spatial resolution of 0.1° x 0.1° and a temporal resolution of 1 hour, making it suitable for capturing variations in rainfall intensity and distribution. The data were used to construct a time series graph of rainfall patterns at the study site, providing essential insight into precipitation dynamics during the observation period.

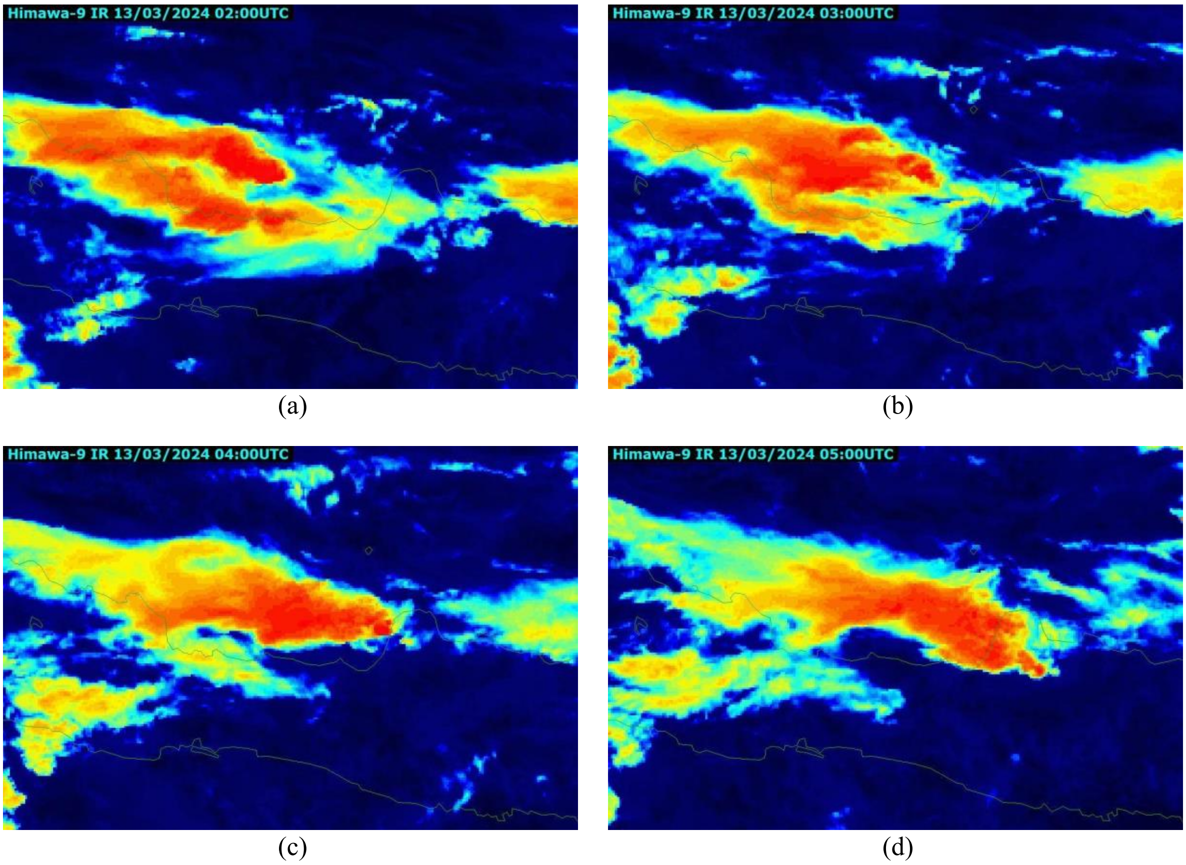
The methodology employed in this study is structured into four distinct phases to systematically investigate the formation and characteristics of squall line phenomena. The initial phase centers on the detection of squall line signatures through the analysis of satellite imagery derived from the Himawari-8 satellite, utilizing the infrared channel (Band-13). This dataset, characterized by a temporal resolution of 10 minutes and a spatial resolution of 2 kilometers, was retrieved via the FileZilla application for the time interval between 01:30 and 07:30 UTC. The imagery was subsequently processed using the Satellite Animation and Interactive Diagnosis (SATAID) software, which enabled the visualization of cloud distribution and cloud-top brightness temperatures. To identify convective cloud regions likely associated with squall line development, brightness temperature (BT) values were analyzed—specifically targeting values less than or equal to -60°C, in accordance with the criteria outlined by Machado (2004). The observed cloud structures were further interpreted and validated based on the squall line pattern characteristics proposed by Bluestein and Jain (1995), which include a linear structure exceeding 100 kilometers in length, a minimum system lifespan of six hours, and the presence of a distinct temperature gradient indicating a convective core surrounded by stratiform cloud cover.

Subsequent analysis focused on atmospheric dynamics to assess the environmental conditions conducive to the development of mesoscale convective systems (MCS). For this purpose, atmospheric sounding data from a location proximate to the observed convective activity was utilized. The data, sourced from the Copernicus ERA5 reanalysis product, were processed into Skew-T Log-P diagrams using the Google Colab platform. These diagrams facilitated the examination of key atmospheric instability indices, including Convective Available Potential Energy (CAPE) to evaluate the potential for convective development, Convective Inhibition (CIN) to quantify atmospheric resistance to upward motion, and the Lifted Index (LI) to assess the degree of atmospheric instability.

In parallel, the spatial and temporal distribution of precipitation associated with the squall line was analyzed using data from the Global Satellite Mapping of Precipitation (GSMaP). This dataset provides high-resolution coverage, with a temporal resolution of 30 minutes and a spatial resolution of 0.1° x 0.1°, enabling a detailed assessment of rainfall patterns. The data were processed to generate rainfall distribution maps and to identify regions of maximum precipitation intensity. For the purposes of this study, heavy rainfall events were defined as those exhibiting intensities equal to or greater than 50.1 mm per hour, consistent with established classification thresholds.

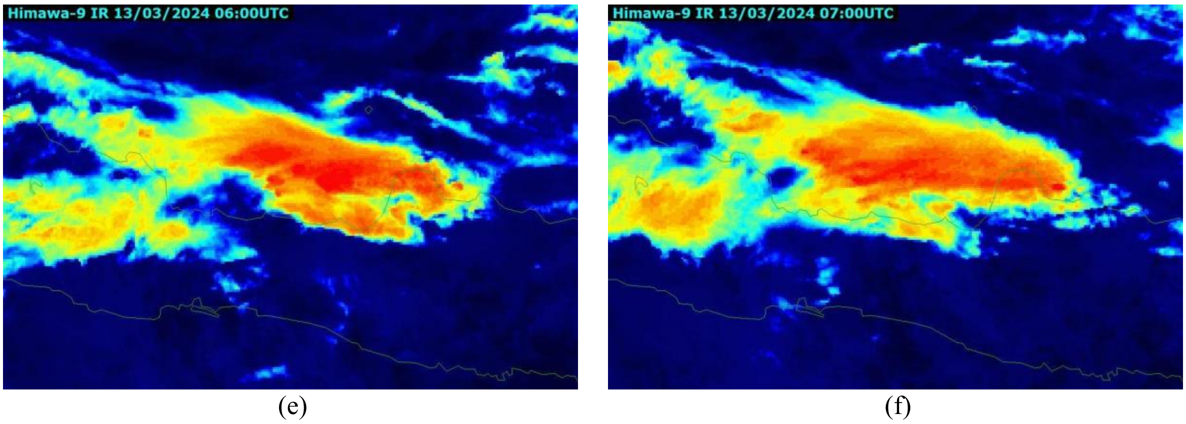
To ensure the validity and coherence of the findings, a final validation stage was conducted. This process involved cross-referencing data obtained from various sources—namely satellite imagery, atmospheric sounding analyses, and GSMaP precipitation data—to verify the consistency of results and confirm the relevance of observed meteorological patterns to the squall line phenomenon under investigation.

III. RESULTS AND DISCUSSION



(a) (b)

(c) (d)



(e) (f)

Fig. 3. Distribution and development of convective clouds from Himawari-9 infrared satellite imagery.

The satellite imagery analysis provides a detailed timeline of the development and progression of the mesoscale convective system (MCS) that formed over the northern coast of Java and affected Semarang and its surroundings. The temporal and spatial characteristics of the system offer valuable insights into the dynamics and severity of the event.

At 02:00 UTC, the presence of significant convective activity over the northern coast of Java, as indicated by orange to red colors on the satellite imagery, represents low cloud top temperatures. These temperatures are indicative of high-altitude cloud tops, often associated with deep convective clouds. This suggests an initial phase of convective activity with strong vertical development, where the thermal contrast between the warm surface and cold cloud tops points to an energetic atmosphere capable of producing heavy rainfall. By 03:00 UTC, the formation of convective cells over the Semarang area indicated an intensification of the convective activity. The cells at this stage were not yet fully organized, signaling the incipient phase of the mesoscale convective system (MCS). This pattern is typical of the early development stages of MCSs, where convection begins to cluster and exhibit the initial dynamics of organization, driven by localized surface convergence and buoyant energy release.

At 04:00 UTC, the convective cloud system showed marked expansion and intensification, with an increase in the area of low cloud top temperatures. This stage represents the transition of the system into a more developed MCS, characterized by enhanced convective updrafts and the consolidation of convective cells. The intensification at this stage aligns with the formation of strong cumulonimbus clouds, further heightening the potential for heavy rainfall and strong winds. By 05:00 UTC, the convective system reached a mature phase, evidenced by a substantial increase in the extent and intensity of low cloud top temperatures. The maturity of the system suggests robust convective activity, with significant hydrometeor loading in the clouds, increasing the likelihood of severe weather phenomena, such as extreme rainfall, gusty winds, and local flooding. The organization of the cloud system at this stage indicates dynamic interactions between environmental factors, including moisture advection, wind shear, and latent heat release.

At 06:00 UTC, the convective system began to exhibit a linear pattern characteristic of a squall line. Squall lines are often associated with sustained convective activity, featuring strong updrafts at the leading edge and extensive stratiform precipitation trailing behind. This structural evolution highlights the influence of vertical wind shear, which organizes the convective cells into a linear configuration, enhancing the system's propagation and impact. The intensification at this stage is critical, as squall lines often produce localized intense rainfall and damaging winds. By 07:00 UTC, the squall line further intensified and expanded, with a broader area of low cloud top temperatures. This indicates the peak intensity of the convective system, with a high likelihood of hydrometeorological hazards, such as extreme rainfall and potentially severe winds. The widespread nature of the cloud system suggests sustained dynamics, including strong inflow at lower levels and robust outflow at upper levels, which maintain the system's strength and longevity.

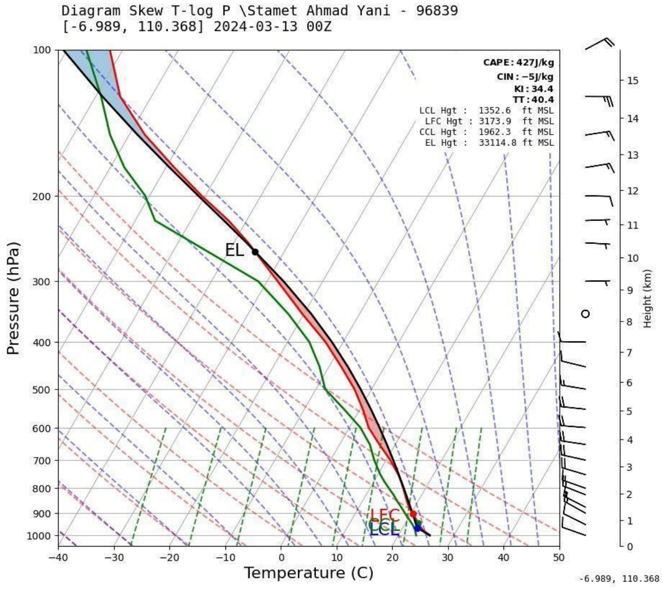


Fig. 4. Skew-T Log-P diagram showing the upper air profile.

Based on the analysis of the Skew-T Log-P diagram, several atmospheric parameters highlight the potential for squall line development and its associated heavy rainfall event. The Convective Available Potential Energy (CAPE) value of 427 J/kg indicates an unstable atmospheric condition conducive to the growth of cumulonimbus clouds, a fundamental component of squall lines. CAPE values exceeding 360 J/kg observed from 00:00 to 12:00 UTC signify significant energy available for convection, which is critical for initiating and sustaining heavy rainfall [22]. This energy allows air parcels to ascend rapidly, fostering the vertical development of convective clouds that are characteristic of squall line systems.

The Convective Inhibition (CIN) value of -5 J/kg is minimal, indicating little resistance to the rising motion of air parcels. This lack of inhibition promotes the formation of deep convective clouds, particularly in the presence of favorable moisture and thermodynamic profiles [23]. CIN values this low reflect an environment primed for convection, where only a small trigger, such as surface heating or convergence, is required to initiate the lifting process. The Lifting Condensation Level (LCL), measured at 1,352.6 ft, further underscores the supportive environment for convection. A low LCL suggests that surface moisture is sufficiently high, allowing condensation to occur quickly as air rises. This rapid condensation facilitates the formation of cumulonimbus clouds, enhancing the convective potential and the intensity of the squall line's rainfall [24]. In tandem, the Level of Free Convection (LFC) at 3,173.9 ft indicates the altitude at which air parcels begin to rise freely due to buoyancy. A low LFC signifies a conducive environment for vigorous updrafts, a hallmark of squall line systems [25]. Another critical factor evident in the diagram is the vertical wind shear, characterized by changes in wind speed and direction with altitude. The increasing wind speeds with height, combined with directional shear, provide the necessary dynamical support for squall line formation. This wind shear organizes the convective system, enhancing the development of strong outflows and facilitating the linear structure typical of squall lines. The strong outflows contribute to the system's propagation and intensify its impact by sustaining the convective cycle.

Overall, the atmospheric profile depicted in the Skew-T Log-P diagram reveals a highly supportive environment for squall line development. The combination of ample CAPE, minimal CIN, low LCL and LFC values, and significant wind shear highlights the critical interplay between thermodynamic and dynamic factors in producing extreme weather events like squall lines. These conditions not only favor the growth of cumulonimbus clouds but also enhance the system's longevity and rainfall intensity, underscoring the potential for severe hydrometeorological impacts.

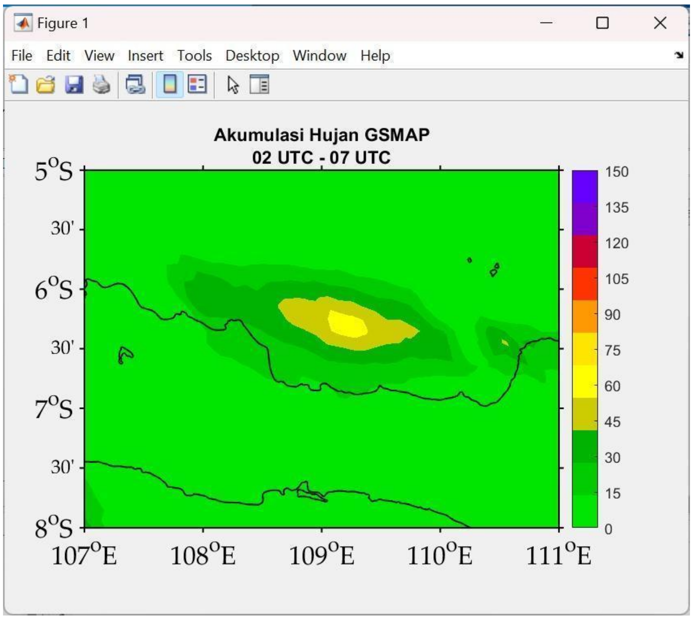


Fig. 5. Rainfall accumulation based on GSMap.

The spatial distribution of rainfall accumulation based on GSMaP data for the period from 02.00 UTC to 07.00 UTC in the area around Semarang reveals an uneven pattern, highlighting the localized nature of the heavy precipitation associated with the mesoscale convective system (MCS). The highest rainfall intensity (>120 mm) was concentrated within the coordinates 6°S to 7°S and 109°E to 110°E. This intense rainfall zone corresponds directly to the core activity of the squall line that developed on March 13, 2024, demonstrating the capacity of such systems to generate extreme weather over a confined area.

The GSMaP visualization, with a color gradient from green (low intensity) to red (high intensity), effectively captures the spatial variations in rainfall. The observed patterns reflect the characteristics of an MCS, where cumulonimbus cloud systems organize into linear or clustered structures, enhancing the potential for short-duration, high-intensity rainfall. The squall line phenomenon exhibited during this event is a classic example, as it aligns with the rapid formation and propagation of convective cells that merge into a larger, more organized system capable of producing severe precipitation over a narrow corridor.

Further analysis of the rainfall distribution suggests that the squall line's orientation and propagation direction were critical in determining the spatial extent and intensity of the precipitation. The alignment of convective cells within the squall line facilitated sustained moisture convergence and upward motion, intensifying rainfall rates. This behavior is consistent with previous studies on squall lines, which identify their linear organization as a primary factor in producing concentrated precipitation zones.

IV. CONCLUSION

This research has analyzed the development and impact of a squall line phenomenon over Semarang on March 13, 2024, using satellite imagery, atmospheric profiles, and rainfall data. The study highlights the critical role of convective cloud dynamics, atmospheric instability, and mesoscale systems in severe weather events. The Himawari-9 infrared satellite imagery demonstrated the sequential development of convective clouds into a mature squall line system. Between 02:00 and 07:00 UTC, significant convective activity was observed, characterized by low cloud top temperatures and the formation of a linear cloud structure. This progression aligned with the established behavior of squall lines, which typically result in heavy rainfall and strong winds.

Atmospheric analysis using the Skew-T Log-P diagram further validated these observations. The CAPE value of 427 J/kg indicated an unstable atmosphere conducive to cumulonimbus cloud development, while the low CIN value (-5 J/kg) and favorable LCL and LFC levels supported the initiation and growth of deep convection. Additionally, vertical wind shear was identified as a key factor in sustaining the squall line system. Rainfall distribution data from GSMaP revealed the intense localized precipitation associated with the squall line, with accumulations exceeding 120 mm in some areas. The alignment of high rainfall intensity with the mesoscale convective system underlines the squall line's contribution to severe weather impacts.

In conclusion, this study demonstrates the capability of integrated observational and analytical tools in characterizing squall line phenomena. The findings underscore the importance of monitoring atmospheric instability and mesoscale dynamics for early warning and impact-based forecasting, especially in regions vulnerable to severe weather events.

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