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The Characteristics of squall line over Indonesia and its vicinity based on Himawari-8 satellite imagery and radar data interpretation

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The Characteristics of squall line over Indonesia and its vicinity based on Himawari-8 satellite imagery and radar data interpretation

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Abstract. Squall line is a rare MCS phenomenon happened in Indonesia. In these recent years, radar showed the existence of squall line pattern on 31 December 2017, 25 and 27 January 2018 in disparate spot in Indonesia. This study aims to find the common characteristic of squall lines that occurs in tropical region of Indonesia. The result shows a persistent elongated convective pattern with the trailing stratiform region extends over 100 km in more than 6 hours in all squall line events observed in this study. The average cloud top temperature below -45ºC indicates an abundant amount of ice crystals. Radar data analysis shows that reflectivity value and surface rainfall intensity in the core part of the squall system always higher than the outer part, with maximum reflectivity value observed on the lower level of the convective cells. Analysis of the vertical structure of squall system shows that height of convective cells on the first squall system reached 17 km, while on the second squall system reached 12 km. The origin place where the squall line formed determines the structure and character of the squall system. These findings show that updraft mechanism on the continental area is generally stronger than around marine areas.

Keywords : Himawari, MCS, squall lines, convective.

1. Introduction

As a "mini" mesocyclonic thunderstorm, squall lines were assessed by many to be the primary host of tornadoes [1, 2]. Tropical squall line is a rare Mesoscale Convective Systems (MCS) phenomenon happened in Indonesia, a region with complexity on its atmosphere dynamics due to its geographic location. The tropical squall line is propagating mesoscale disturbance, commonly referred to as squall system, consists of cumulonimbus cloud elements and extensive precipitating anvil cloud [3] trails the squall line. Houze [4] and Zipser [5] further broadened the concept of the squall line to include the anvil and stratiform precipitation with a cool air often found behind the gust front as part of the squall line system. Thus, strong squall lines may contain supercells as building blocks, while weaker squall lines composed mainly of ordinary cells [6] or even precipitation elements forced by instabilities not exclusively due to gravity, such as conditional symmetric instability [7].

Further research on squall system was studied by Bluestein and Jain [8] and references therein. There are four classifications of squall line development: broken line squall lines, back-building squall lines, broken-areal squall lines, embedded-areal squall lines. The four-ways squall line formation as described by Bluestein and Jain [8] depicted in Figure 1. The broken-line and back-building formation processes are easily discerned in visible satellite images, but broken-areal and embedded-areal developments are not. All types of squall lines form in a conditionally and convectively unstable atmosphere which is characterized by strong vertical shear and turning of the shear vector with height at low levels, and weaker shear and only slight turning aloft. In addition, most lines formed within a range of 200 km, where the radar-beam resolution is fine enough to detect the appearance of new cells.

Fewer studies were conducted to examine the formation of squall line in tropical regions rather than in the midlatitude region. Houze [4] examined the structure and dynamics of tropical squall line system and found that the downpour of heavy precipitation below the sloping updraft of squall line system contained a convective-scale downdraft in the heavy rain zone which spread out at low levels. While, the precipitation falling from the anvil cloud was stratiform in character. Further studies of Gamache and Houze [9] showed that the squall line region was characterized by boundary layer convergence, which fed deep convection updrafts. The circulation in the anvil region, on the other hand, was characterized by mid-level convergence, which fed a mesoscale updraft within the anvil cloud and mesoscale downdraft below the anvil.

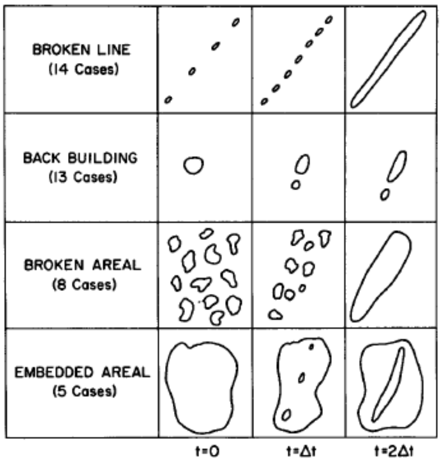

Figure 1. Idealized depiction of squall-line formation [8].

Although there have been several case studies about squall lines in the tropical region, there has been no systematic identification on its characteristics. Therefore, the purpose of this study is to examine the characteristics of tropical squall line by optimizing the use of infrared channel of satellite and radar data interpretation to identify the dynamic aspects. Combining satellite (upper-atmospheric observation) and radar (land-based observation) will give detail depiction of the squall system that occurred in Indonesia. The importance of understanding the characteristics of these disturbances and their dynamic aspects are to give wider insight on weather forecasting skills and provide a chance for doing further research of this rare MCS phenomenon.

2. Data and Methodology

2.1 Research sites

This study was conducted in two regions, both in land and water area in Indonesia, where squall lines system formed. The first squall system observed over South Sumatra region, located near Bukit Barisan mountains on 31 December 2017. While the second and third squall lines system observed almost in the same area around Java sea, located near Kalimantan Island. The second squall line system occurred on 25 January 2018, while the third squall system occurred on next two consecutive days of 26 – 27 January 2018. More information about research sites can be seen in Figure 2.

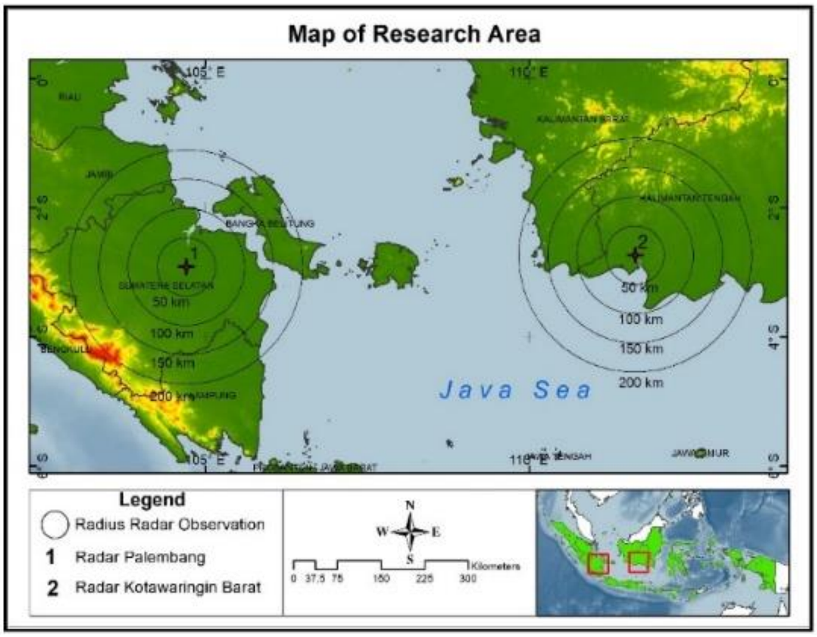

Figure 2. Research area awas conducted near Sumatra and Kalimantan

2.2 Satellite image data

This study focused on optimizing the use of visible (VS) and infrared (IR) channel via WMO Information System (WIS) portal. The other satellite product that used in this study is High-resolution Cloud Analysis Information (HCAI), derivation product from Himawari-8/9 satellite imagery. These data obtained from subdivision management of weather satellite image of Indonesian Agency for Meteorology Climatology and Geophysics (BMKG). Himawari WIS product has spatial resolution of 4 km and temporal resolution of 10 minutes. Satellite Animation and Interactive Diagnosis (SATAID) then used to process these satellite data. Dewita [10] stated that visible channel of the satellite was really effective to detect squall line events in daylight.

2.3 Radar data interpretation

Radar provides a good temporal and spatial resolution and able to give 3-dimension looks of a squall system. Another research using radar to study the convective cells in the mesoscale system and found that vertical profiles of radar reflectivity in Global Atmospheric Research Programme's Atlantic Tropical Experiment (GATE) cells exhibit generally modest reflectivity at low levels, decreasing rapidly with height above the freezing level [11]. Further studies showed that Gematronik Radar was competence enough for analysing the structure of squall line [10]. Radar data on 31 December 2017 over South Sumatra region observed by radar located in Palembang, while radar data on 26 and 27 January 2018 obtained C-Band Gematronik Weather Radar from meteorological station of Iskandar Kotawaringin Barat. Unfortunately, radar data on 25 January 2018 was missing due to technical issues. This data obtained using Gematronik radar then processed using Rainbow software. Gematronik radar used two range operational radar, 240 km for intensity observation and 120 km for observation resolution and better analysis [12].

3. Characterization of Squall Line System on Satellite Images

3.1 Squall Lines Observation

Hamilton and Archbold [13] defined squall lines as a typical tropical squall line consists of a row of cumulonimbus clouds forming at the edge of a downdraft region. This description was highly matched with satellite observation on the visible channel in this study, where cumulonimbus clouds, which depicted as a lumpy texture of cloud, observed in an elongated form of the cloud with trailing stratiform surround it. In some cases, the squall system forms a bow echo model, a special case when the squall line becomes bowed [10]. This occurs when the rear inflow jet is very strong, which can be identified on the radar as rear inflow notch, a weak echo region then shifted behind the core of the bowed convective line.

Based on the subjective interpretation of cloud types using the visible channel, a very thick and lumpy texture of cloud observed as an elongated convective line during the occurrence of the squall line system. The bright look showed that the cloud system consists of ice crystal on its top, reflected almost all of the light to the direction from which it comes. On the formation of the first squall line system on 31 December 2017, discrete convective cells observed for the first time at 09.10 UTC and continued to grow, until reached its mature stage at 12.30 UTC as shown in Figure 3. As it grows, the system development from time to time showing almost no movement, the movement only occurs is caused by the extend of clouds development, wider and spread [14]. The mature stage of this convective cloud indicated by a well-defined cloud edges with cauliflower looks that generated a line connection of convective cloud, with no gaps within the system. Interpretation of visible channel at 12.30 UTC was not possible since this channel strongly depends on the existence of solar radiation. The only movement caused by cloud development, the MCC system could persist in exact same location from growth phase until dissipating phase. This squall line might form due to monsoon Asia that hit the extent of Bukit Barisan mountains, resulting in the formation of elongated convective cloud over South Sumatra region. Another discrete cell started to form over the Java sea near Kalimantan on 25 January 2018, reached its mature squall systems stage at 02.00 UTC. While, the third squall line observed in this study, appeared as the convective cloud for the first time on 26 January 2018 at 23.00 UTC, reached its mature stage on 23.30 UTC and persisted until the next day, 27 January 2018.

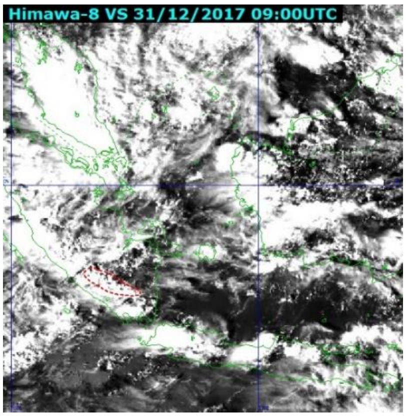

Figure 3. Visible channel of Himawari Satellite in the formation stage of squall lines over South Sumatera Island.

3.2 Objective Analysis of Squall Lines Structure

The objective analysis was done using HCAI products of Himawari satellite observation. This method used to ensure the type of clouds composing the whole structure of squall line formation, although the stratiform region was very hard to be observed using this method. The first squall lines showed that the convective cells located at the front edge of the system, surrounded by dense cloud (mixed cloud between cumulonimbus and high cloud region, hard to differentiate each type). This squall lines system was comprised of mostly individual convective elements. The stratiform region could not be detected. The second squall lines system showed that the squall system composed mostly by convective cells,

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broaden dense cloud area surrounding the convective area, and leading stratiform near the edge of the convective cloud. Houze et al. [15] identified the leading-line trailing stratiform (TS) structure as the most common organization of mature MCS. Further studies by Parker and Johnson [16] also recognized leading stratiform (LS) and parallel stratiform (PS) as a common arrangement of the convective line system. The third squall lines system showed that the squall system mostly composed by dense cloud and a small portion of convective cloud during the development of the squall lines system.

Another objective analysis on the IR channel used to understand the vertical wind profile of the squall system. Vertical wind analysis that used Numerical Weather Prediction (NWP) product, Global Spectral Model (GSM) on the first and second squall system, showed a change of wind speed and direction with the height in the atmosphere (commonly known as wind shear) observed at altitude about 300 – 400 mb, the wind speed increase along with the increase of the altitude. While the last squall line system in this study showed that wind shear occurred at altitude about 400 – 500 mb. This analysis showed that the three-squall line system has the same wind shear pattern at altitudes between 300 – 500 mb.

3.3 Squall Line Coverage Area

3.3.1 Typical length of squall lines system. On 31 December 2017, the typical length of the squall system formed over South Sumatra region was about 138 km. The typical length of the second squall systems was about 224 km, which is the longest linear type of squall lines formed during this study. The third squall systems formed around the same location with the second squall systems have a typical length of 109 km. It was the shortest squall system during this study. Thereby in general, the typical length of squall lines system form in Indonesia is about more than or equal to 100 km. However, these findings cannot be generalized because the sample size is too small to be statistically significant.

3.3.2 Squall line system total area. By adopting Maddox [17] research on characterizing the MCC as a convective system persisted for more than 6 hours, this study also defines the total coverage squall system area which has continuously low IR black-body temperature $T_{BB} \leq$ -52°C, $T_{BB} \leq$ -32°C, and $T_{BB} \leq$ -40°C. When a large portion of squall systems have $T_{BB} \leq$ -52°C, it indicates that the system is active and precipitation is falling over significant area, $T_{BB} \leq$ -32°C was a depiction of mature stage which indicates an average cold cloud shield area, and when most squall lines portion have $T_{BB} \leq$ -40°C, all the water droplet content in that cloud system will suddenly change into an ice form [18]. Ahrens also emphasized that clouds which have a cloud top temperature of -40°C composed mainly from ice crystals [19].

The total area of cloud shield with $T_{BB} \leq$ -32°C on the first squall system formed on 31 December 2017 was 115296 km^2, $T_{BB} \leq$ -40°C was 79632 km^2, while the total cloud coverage with $T_{BB} \leq$ -52°C was 74016 km^2. The second squall system showed that the total area of cloud shield with $T_{BB} \leq$ -32°C was 113440 km^2, $T_{BB} \leq$ -40°C was 77136 km^2, while the total cloud coverage with $T_{BB} \leq$ -52°C was 46624 km^2. The mature stage of the third squall system showed that the total area of cloud shield with $T_{BB} \leq$ -32°C was 141648 km^2, $T_{BB} \leq$ -40°C was 87232 km^2, while the total cloud coverage with $T_{BB} \leq$ -52°C was 27680 km^2. From this observation, we can deduce that the squall lines system form in Indonesia has the total area of cloud shield of more than or equal to 100000 km^2 for $T_{BB} \leq$ -32°C, more than or equal to 70000 km^2 for $T_{BB} \leq$ -40°C, and more than or equal to 20000 km^2 for $T_{BB} \leq$ -52°C.

Table 1. Total area coverage by squall lines system based upon analysis of IR satellite imagery data.

	31 December 2017	25 January 2018	27 January 2018
$T_{BB} \leq$ -32ºC	115296 km^2	113440 km^2	141648 km^2
$T_{BB} \leq$ -40ºC	79632 km^2	77136 km^2	87232 km^2
$T_{BB} \leq$ -52ºC	74016 km^2	46624 km^2	27680 km^2

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3.3.3 Top cloud temperature and lifetime. This study identifies the top cloud temperature and the lifetime of three squall systems formed in Indonesia. The first squall systems formed on 31 December 2017 showed that the convective system persists for about 12 hours with the average cloud top temperature around -67.8°C and its minimum temperature is -86.8°C as shown in Figure 4.

The second squall systems observed on 25 January 2018 showed that the convective system persists for about 6 hours with the average cloud top temperature around -45°C and its minimum temperature is -74.5°C. The characteristics of the third squall system which formed on 27 December 2018 showed that the convective system persists for about 6 hours with the average cloud top temperature around -50.9°C and its minimum temperature is -85.1°C. If it is assumed that the cloud system only consists of the pure water droplet, freezing will occur at temperature about -40°C [18].

In fact, there is an abundant amount of cloud nuclei, ice nuclei, and aerosol in the atmosphere which accelerates the formation of a cloud system. The top cloud temperature of these three squall lines system showed a temperature more than -40°C, means that the top cloud layer mostly consists of ice crystal. The thick cloud which inherit the height of high clouds with its top cloud temperature is less than -40°C was a brief evidence to deduce it as a convective, cumulonimbus cloud.

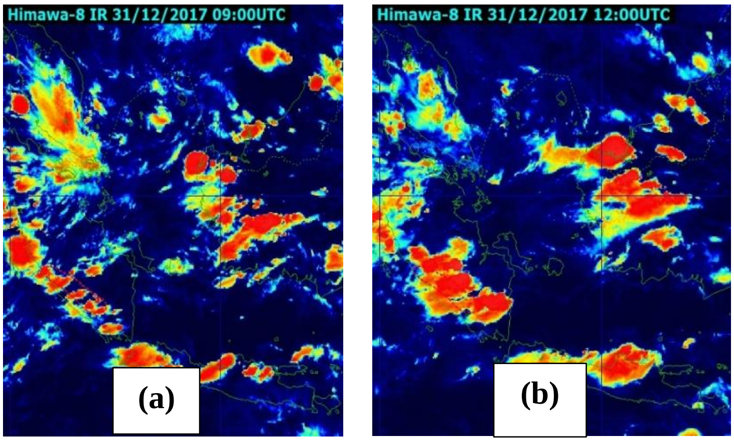

Figure 4. IR channel from Himawari-8 Satellite, (a) shows the growth stage of system and (b) shows the mature stage of the system. Red color show the convective cloud and very cold temperature.

Table 2. Identification of the lifetime and top cloud temperature of squall line systems based upon analysis of IR satellite imagery data.

	31 December 2017	25 January 2018	27 January 2018
Lifetime (hours)	12	6	6
Top cloud average temperature (°C)	-67.8 ºC	-45 ºC	-50.9 ºC
Minimum top cloud temperature (°C)	-86.8 ºC	-74.5 ºC	-85.1 ºC

4. Dynamic Aspects of the Squall Line System Using Radar Data Interpretation

4.1 Reflectivity Pattern of the Squall Line System

The appearance of discrete convective cells forming at nearly the same time on the first squall system started to appear at 09.10 UTC. Initially, this cell created a linear pattern of the convective line moved from south-west to north-east and reached its mature stage at 12.30 UTC in the form of bow echo, as shown in Fig 2a. The front edge of its mature element, as illustrated by Houze [4], had maximum reflectivity value around 40 – 55 dBZ and thereby, identified as the convective region of the squall system (region of heavy convective showers), showed the storm motion as well. This cloud system also consisted of the region of trailing stratiform, some defined it as anvil region, right behind the convective region indicated by lower reflectivity value around 10 – 30 dBZ. As the squall system moved, the trailing stratiform region became wider. Reflectivity pattern of the third squall system initially created a linear form. This pattern started to appear at 22.00 UTC on 26 January 2018 and continued to grow until the next day.

This system became wider and started to move to north-east. This squall system had the same pattern with the first squall line formed over South Sumatra, where the reflectivity of the convective region was around 35 – 50 dBZ and the trailing stratiform was around 10 – 30 dBZ. As time went by, this squall system showing a bow echo form at 23.30 UTC, a circular shape of tropical squall line illustrated by Maddox [17].

According to squall lines classification identified by Bluestein and Jain [8], the first squall lines categorized as a broken line formation. These squall systems appeared as a line of discrete cells, each cell forming at nearly the same time and transformed the line of convective cells into a solid line as the area of each existing cell expands and new cells develop in between the older cells. This type of squall line formation has been documented in Figure 5a. The third squall line system observed in this study was a back-building squall line formation. This type of squall system consists of the periodic appearance of a new cell upstream, relative to cell motion, from an old cell, and the resulting merger of the new cell with the old cell as the former expands in the area and moves into the latter. Although this process is usually initiated from a single cell, it can also occur to a group of widely spaced (much longer than the cell length) cells, each of which can back build to form a line or line segment. This type of squall line formation has been well-documented in Figure 5b. Besides using CMAX data, squall line types can be determined by interpreting visible channel data. These two-data inherit the same pattern that showed the best performance on examining the ways in which the “building block” that formed the mature squall line system initially become organized into a line. Due to the absence of radar data on 25 January 2018, the type of the second squall line was determined solely by analysing visible channel. This analysing showed that the second squall line systems categorized as a broken line type.

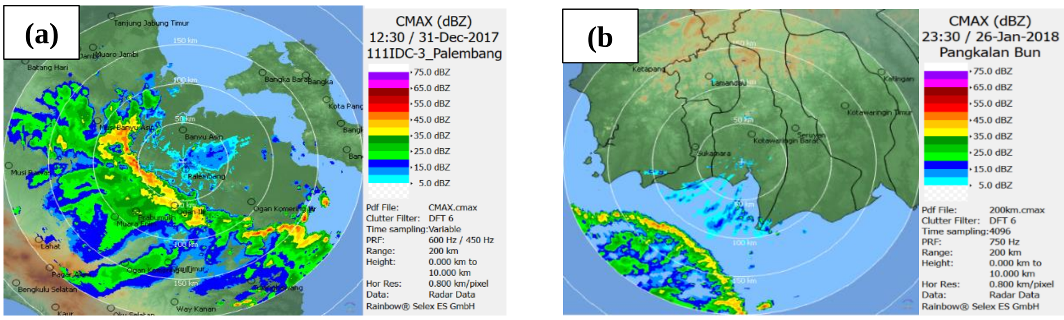

Figure 5. CMAX product analysis showing the range of reflectivity between the first and third squall line system observed in this study; (a) reflectivity pattern of the first squall line system formed over South Sumatra at 12.30 UTC, (b) reflectivity pattern of the third squall line system formed over Java sea near Kalimantan at 23.30 UTC.

4.2 Vertical Profile of the Squall Line System

Analysis of the vertical structure of the first squall system showed that the base height of reflectivity was around 1 – 4 km above the ground. This height then became smaller, reached 3 km at 08.00 UTC and less than 1 km at 13.00 UTC. While the top height of this reflectivity reached 17 km which can be indicated the top of cumulonimbus where the anvil region spread out around this height (Figure 6a). The maximum reflectivity value, around 50 – 55 dBZ, located at the height of 2 – 6 km. Szoke and Zipster [11] stated that this could happen because a weak updraft caused the maximum reflectivity value located at low levels because water droplets could not be lifted up. However, VCUT analysis at 09.00 UTC showed a different result, where the maximum reflectivity pattern located a height of 19 km. This change indicated that the updraft force became stronger. While, the reflectivity of the third squall, indicated its vertical profile, was in the range of 45 – 50 dBZ at 4 – 6 km, where the lowest reflectivity was 5 – 20 dBZ. If compare to the first squall line that formed over land area, this third squall had lower reflectivity.

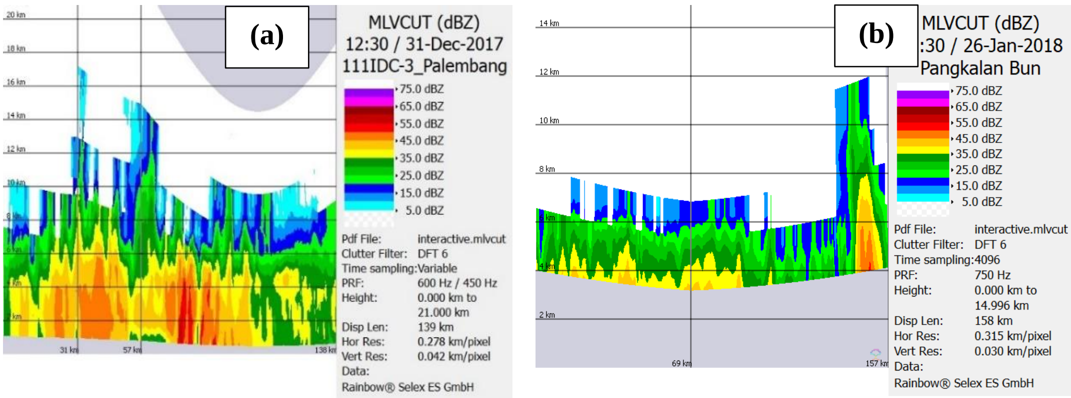

Figure 6. Vertical structure or cross section of the first and third squall line system can be identified using VCUT product of a radar data; (a) VCUT product along the front edge of the squall system in its mature stage, (b) Multi Line VCUT (MLVCUT) product along the front edge of the third squall system. This vertical section has taken from two lines following the bowed form of the squall lines system.

In general, the base height of the third and first squall system nearly the same, but the top height of this third squall system was lower than the first squall system, it was about 12 km at 22.30 UTC as shown on Figure 3b.

4.3 Surface Rainfall Intensity Analysis

Surface Rainfall Intensity (SRI) radar product indicated rainfall intensity at a given altitude above the earth's surface. In this study, analysis on SRI was set at an altitude of 3.5 km above the surface so that it could reach a distance at radius of 180 km, where the squall system began to form. The value of rainfall intensity in the initial phase of squall formation ranges from 0.2 – 0.8 mm/h on the outer side of the system, while it reached 12.6 – 25.1 mm/h in the core part of the system.

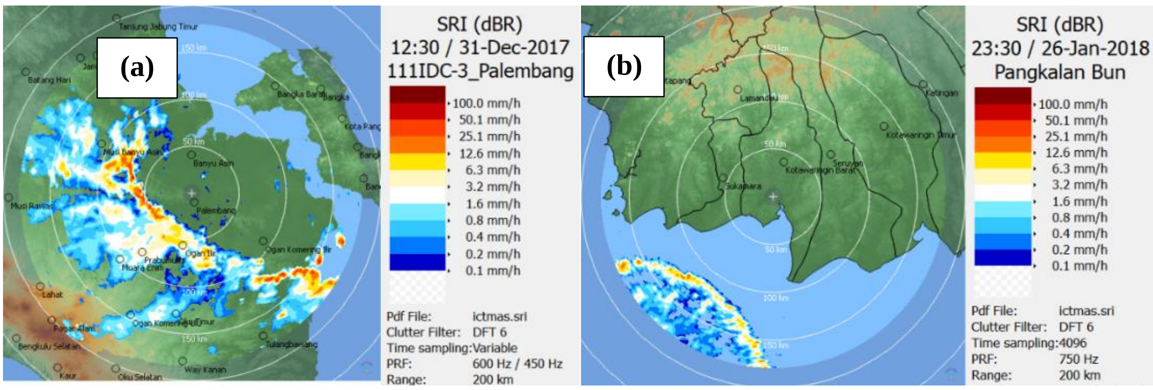

Figure 7. Surface rainfall intensity analysis along the squall system identified using SRI radar data. This product can estimate the amount of water that will precipitate at a constant height above the ground; (a) SRI product showing the maximum value of surface rainfall intensity of the first squall line system over South Sumatra region at 12.30 UTC, (b) SRI product showing the maximum value of surface rainfall intensity of the third squall line system over Java sea, near Kalimantan at 22.30 UTC.

The mature stage of first squall system occurred at 12.30 UTC with rainfall intensity in the core part of the system reaching 12.6 – 50.1 mm/h, while it reached 0.2 – 12.6 mm/h on the outer part (Figure 7a). The rainfall intensity of this squall system started to decrease afterward at 12.50 UTC. Surface rainfall intensity in the core part of the squall system seemed to decrease, but the coverage area increased. The decrease in rainfall intensity continued to occur until the system was extinct at around 13.40 UTC.

Analysis of the SRI of the third squall system (Figure 7b) showed that the rain intensity of the system reached 0.2 – 25.1 mm/h at 22.30 UTC. The SRI value seemed to increase along with the growth of the squall system. The highest rainfall intensity in this squall system occurred at 23.30 UTC, where the rainfall intensity on its core part reached 6.3 – 25.1 mm/h and the outer side of squall system reached 0.2 – 6.3 mm/h.

5. Discussions

Based on the analysis using satellite and radar data, the origin place where the squall line system formed to influence the formation structure of the system. Analysis on the cloud temperature using IR channel of Himawari-8 satellite data showed that the average cloud top temperature of the three-squall line system in this study was less than -45°C, while their average minimum temperature was less than -70°C. The squall system which had the lowest cloud top temperature is the first squall line system formed over South Sumatra region, basically categorized as continental area.

Moreover, analysis of the vertical structure of squall system showed that the height of convective cells on the first squall line system over South Sumatra reached 17 km, while the height of convective cells on the second squall system reached 12 km. Based on this result, we can know that the height of the convective cloud in a squall line system that formed over the continental region was higher than those which formed over marine areas. Analysis of the CMAX product showed that the cloud convective region in the first squall line system that formed over South Sumatra had higher reflectivity value than the third squall line system that formed over the Java Sea, basically categorized as marine areas. The reflectivity value in the core part of the first squall system was about 40 – 55 dBZ, while it was about 35 – 50 dBZ in the core part of the third squall system. The maximum reflectivity value of the first squall system was observed at 2 – 6 km above the base of the cloud, while the maximum reflectivity value on the third squall system was observed at 4 – 6 km. Generally, the maximum reflectivity value was observed at a lower level of a convective cloud system. This could happen because the liquid water content on the lower level of convective cloud was commonly the highest. When the updraft force became stronger the maximum reflectivity will be shifted on a higher level along with the more water droplet concentration that lifted up into a higher level. Furthermore, analysis on the surface rainfall intensity showed that the rainfall intensity of the first squall line system which formed over the continental region was higher than rainfall intensity of the third squall line system which basically formed over marine areas. The maximum rainfall intensity on the first squall line system reached up to 50.1 mm/h, while on the third squall system was only about 25.1 mm/h.

These findings showed that the updraft mechanism on the continental area is generally stronger than around marine areas. This could happen because there is no topographic factor involved in the cloud formation processes over marine areas, while the topographic complex over continental area caused frequent turbulences that induce stronger updraft. Furthermore, most of the marine clouds have droplet concentrations less than 100 cm^{-3}, and none has a droplet concentration greater than 200 cm^{-3}. In contrast, some of the continental cumulus clouds have droplet concentrations in excess of 900 cm^{-3}, and most have concentrations of a few hundred per cubic centimeter [20]. Thereby, many more droplets compete for the available moisture in continental clouds than in maritime clouds, and they are smaller consequently [18]. Ryan et al. [21] confirmed that maritime clouds usually have a broader size spectrum than continental clouds. This broader size caused condensation process became more intensive, resulting in the formation of narrower convective cloud with smaller updraft compared to the formation of convective cloud over the continental area. In addition, the condensation nuclei concentration above continental area was higher and diverse in size due to human activities, while the size and type of this nuclei commonly the same above marine areas. This is why the cloud formation processes that form the squall line system over continental and marine areas inherit different structure and character.

6. Summary

Tropical squall line system that formed over Indonesia, both in continental and marine area, inherit commonly the same pattern, where the system comprised of the elongated convective line (core part of the squall system) and trailing stratiform region and the anvil region (outer part of the squall system). However, the type of squall line formation was diverse, the first and second squall line formation categorized as a broken line, while the third squall system indicated a back-building squall line formation. Generally, the wind shear pattern on these three-squall line system occurred at height 300 – 500 mb.

In general, the typical length of the squall line system in this study was more than 100 km and the total coverage squall system area with $T_{BB} \leq$ -32°C ranged from 113440 – 141648 km^2, with $T_{BB} \leq$ -40°C ranged from 77136 – 87232 km^2, and with $T_{BB} \leq$ -52°C ranged from 27680 – 74016 km^2. The average of cloud top temperature of the three-squall line's system observed in this study was -67,8°C, -45°C, and -50.9°C, consecutively. Based on CMAX radar data analysis, the reflectivity value in the core part of the first squall system was around 40 – 55 dBZ, while on the third squall system was around 35 – 50 dBZ. The reflectivity value on the outer part of the squall system on this two-squall system was around 10 – 30 dBZ, lower than the core part of the system. VCUT product analysis showed that the peak height of the convective cloud on the first squall reached up to 17 km with the maximum reflectivity of 50 – 55 dBZ at 2 – 6 km, while on the third squall system was lower at about 12 km, with maximum reflectivity of 35 – 50 dBZ at 4 – 6 km. Furthermore, analysis on the surface rainfall intensity showed that the rainfall intensity in the core part of the squall system was always higher than the outer part of the system. Surface rainfall intensity on the core part of the first squall system was about 12.6 – 50.1 mm/h, while the surface rainfall intensity of the third squall line system was lower in value around 6.3 – 25.1 mm/h.

The origin place where the squall line formed determines the structure and character of the squall system. Convective cloud formation was strongly developed above continental areas rather than marine areas, thereby the squall line system formed over the continental region had higher cloud top with more intense liquid cloud water content. This happened because of several factors, such as the more complex topographic structure of continental region, higher concentration of cloud condensation nuclei and aerosol, and larger average size droplet spectrum which composed a convective cloud system.

Acknowledgments

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