Kinematic and Thermodynamic Structures of Mesoscale Convective Systems During Heavy Rainfall in Greater Jakarta

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Abstract

A mesoscale convective system (MCS) is a large complex convective cloud system associated with a contiguous rainfall area that contributes significantly to heavy rainfall. This study analyzed the kinematic and thermodynamic structures of MCS during a heavy rainfall event. The MCSs that coincided with the heavy rainfall event and covered GJ occurred on January 17, 2013, 2014, and February 9, 2015. The three MCS cases were described from satellite observations over GJ during heavy rainfall. The main data consisted of satellite cloud top temperatures and national weather service soundings. We found a cloud shield with a temperature $\leq 221$ K size and size less than 30,000 km$^2$ at the mature stage of the MCS. Low moisture convection was unstable prior to MCS development. The warm moist air at 500–400 hPa could contribute to heavy rainfall above GJ. We suspect that the strong low-level convergence winds produced an updraft, and high moist air led to a developing convective cloud. The moist atmosphere on the third MCS was not always higher than others, but wind was low. These conditions caused the high intensity of heavy rainfall that occurred in GJ on the third MCS.

Introduction

Greater Jakarta (GJ) is located on the northwest coast of Java Island, Indonesian Maritime Continent (IMC). In this area lies the economic and political capital of Indonesia. Thirteen rivers intersect in this area. In the middle of January 2013–2014 and the beginning of February 2015, GJ experienced remarkable flood events. During these events, heavy rainfall often occurred in the vicinity of GJ. Table 1 contains daily rainfall data recorded by weather stations. In Kemayoran, on January 17, 2013, approximately 236.3 mm daily rainfall was observed. Kemayoran
then recorded 234.0 mm of rain on January 17, 2014. On February 9, 2015, Tanjung Priok and Kemayoran recorded 339.0 and 271.0 mm of daily rainfall, respectively. At least 30 s of sub-districts and more than 100 urban villages were flooded based on data from the National Board for Disaster Management (BNPB; source data: http://dibi.bnpb.go.id).

Previous studies have described the important role of the strong trans-equatorial Asian winter monsoon flow in the formation up to heavy rainfall over West Java [1–3]. Intense low-level wind convergence and strong vertical wind shear over Java Island are developed due to the constant northwesterly wind near the surface over the Java Sea. Hamada et al. [4] showed that strong heavy precipitation can occur on the western Java Island (cold, neutral and warm) in all phases of the El Niño/Southern Oscillation (ENSO). Wu et al. [5] investigated the impact of an active phase of the Madden–Julian oscillation (MJO) on heavy rainfall in January 2013. Their results suggested that a strong influence on the development of heavy rainfall over western Java Island is caused by the northwesterly wind near the surface and enhances the eastward propagation of an active phase of the MJO.

The interaction between MJO and the diurnal cycle is complicated [5–7]. These scale interactions are an integral part of the convection, precipitation, and circulation properties of the region [8, 9]. The convective clouds in GJ are usually developed by moist sea breezes on heated topography (mountain sides) every evening and move toward the coast with precipitation [1, 10–12].

The organization of convective systems such as mesoscale convection systems (MCSs) provides a major contribution (60%–75%) to heavy rainfall events [13, 14]. According to Houze [15], MCS is a large convective cloud system associated with a rainstorm complex that creates a contiguous precipitation area of approximately 100 km in a horizontal scale. Considering the importance of MCSs for heavy rainfall events [13, 14, 16–18], an investigation of their development is essential. Previous studies have described the morphology and characteristics of MCSs [18,19], which account for a large amount of precipitation.

The convective system phenomenon associated with heavy rainfall in GJ should be considered in future work. However, only few studies analyzed MCSs in the IMC (e.g., [20–25]), mainly in GJ. In this paper, we discuss the developmental mechanisms of MCS in heavy rainfall events. The present work focused on the observed kinematic and thermodynamic structures of three mature MCSs. We analyzed how variations in vertical motions affected convection within the circulation of the three MCSs. Section 2 describes the observation data and methodology. The kinematic and thermodynamic structures of MCSs studied during the heavy rainfall between 2013 and 2015 are described in Section 3.

### Data and Study Method

Tropical MCSs have been extensively studied (e.g., [20–27]) using various observations, such as surface-based (e.g., [28]), aircraft radar (e.g., [29]), and satellite data (e.g., [20–25, 30]). To identify the MCSs in this study, infrared data from Multi-functional Transport Satellite (MTSAT) images were used. The hourly infrared MTSAT images were obtained from the Research Institute for Sustainable Humanosphere database of Kyoto University [31]. The equivalent black-body temperature (Tb) of the cloud top temperature, which is related to the convection system distribution, was derived from the infrared data.

The method used to identify MCS in this study was the “Grab ‘em, Tag’ em, Graph ‘em” (GTG) algorithm, Graph Theory [24, 32, 33]. A convection element was considered MCS if it covered at least 2,400 km² for at least 3 h. Therefore, each deep convective cloud with a cold cloud top of Tb ≤ −52° C (221 K) and a spatial coverage of more than 2,400 km² was tracked and classified. The choice of the temperature threshold was arbitrary, but this value was frequently used (for discussion of the choice of temperature thresholds, see [34]).

The vertical sounding data from Cengkareng (96749) station was used to determine the atmospheric conditions within the convection system. The zonal and meridional wind components, mixing ratio, and equivalent potential temperature (θ-e) values were extracted from the sounding data to study the kinematic and thermodynamic structures of the MCSs.

| Heavy Rainfall Events | 1       | 2       | 3       |
|-----------------------|---------|---------|---------|
| Date (mm/dd/yyyy)     | 01/17/2013 | 01/17/2014 | 02/09/2015 |
| Daily rainfalls (mm): |         |         |         |
| Tanjung Priok         | 190.0   | 150.0   | 339.0   |
| Cengkareng            | 166.7   | 72.0    | 111.3   |
| Kemayoran             | 236.3   | 234.0   | 271.0   |

**Table 1. Properties of Each Heavy Rainfall. The Date is in the Format Month/Day/Year (mm/dd/yyyy) and Specifies the Valid Time of Heavy Rainfall from Observations in Tanjung Priok, Cengkareng, and Kemayoran**
Figure 1. Study Area of Greater Jakarta as Part of the Indonesian Maritime Continent. The Triangles are the Meteorological Stations Used in the Study (i.e., Port of Tanjung Priok, Soekarno–Hatta Airport Cengkareng, and Jakarta Observatory Kemayoran)

The study area extended over 106.4° E – 107.2° E and 6.06° S – 6.76° S, covering the entire GJ region (Figure 1). The 3 h rainfall data from three meteorological stations of the Indonesian Meteorological Climatology and Geophysics Agency (BMKG) around GJ where used to analyze the time series of precipitation. The stations were (1) Port of Tanjung Priok (106.867° E; 6.100° S), (2) Soekarno–Hatta Airport Cengkareng (106.650° E; 6.117° S), and (3) Jakarta Observatory Kemayoran (106.583° E; 6.183° S). This study focused on the development of MCS in heavy rainfall from mid-January 2013–2014 to early February 2015.

Section 3 describes the role of some specific wind and heat levels. We also used Japanese re-analysis of 55 years (JRA-55), available at 6 h intervals with a horizontal-resolution of 1.25° [35, 36], to show the evolutionary profile of convective cells.

Results and Discussion

The MCS that produced the heavy rainfall on January 17, 2013, was the conglomerate of two different convective clouds (Figure 2a). The first cloud organized over the Sunda Strait on the evening of January 16 and then slowly spread northeastward. The second convective cloud developed on the evening of January 16 across the Java Sea and then slowly flowed southwestward into GJ. Both convective clouds merged at 02:00 LT, January 17, 2013. The 24 h accumulated precipitation on January 17, 2013, was not less than 160 mm at Kemayoran. The highest 3 h rainfall recorded on January 17, 2013 (08:00–10:00 LT) was 147 mm at Kemayoran. The highest 24 h accumulated rainfall levels at Kemayoran, Cengkareng, and Tanjung Priok on January 17, 2013, were 193, 133, and 119 mm, respectively.

Before the heavy rainfall on January 17, 2014, an intense MCS developed on the evening of January 16 across the Sunda Strait, which then spread eastward into GJ (Figure 2b). The second MCS showed stronger and more durable convection (Table 2) than the first MCS, but precipitation was low (Table 1). During January 14–18, 2014, the diurnal variations and average rainfall around GJ were low (Figure 3b). The second MCS showed that the identified convective clouds were wider and cooler than those of the other MCSs.

The precursor of the third MCS to heavy rainfall on February 9, 2015, developed over Lampung on the evening of February 8 (Figure 2c). The convective cloud

Figure 2. Hovmoller Diagram at Latitude (5.5° S – 6.5° S) Average of Tb (Shaded) and TRMM (Contour) during a) January 17, 2013, b) January 17, 2014, and c) February 9, 2015. The Study Area is Denoted by two Green Vertical Dotted Lines

Table 2. Mature Stage Properties of Each MCS Events. Date is in the Format Month/Day/Year (MM/DD/YYYY) and Indicates the Validity Period of the MCS Events from Tb Data

| MCS Events               | 1       | 2       | 3       |
|--------------------------|---------|---------|---------|
| Date (mm/dd/yyyy)        | 01/17/2013 | 01/17/2014 | 02/09/2015 |
| Initiation stage (LT)    | 0000    | 1900    | 2200    |
| Mature stage (LT)        | 0400    | 0700    | 1000    |
| Dissipation stage (LT)   | 1100    | 1500    | 1300    |
| Area                     | 37,613 km² | 50,782 km² | 28,229 km² |
| Average Tb               | 210 K   | 208 K   | 211 K   |
| Eccentricity             | 0.65    | 0.25    | 0.84    |
spread southeastward into GJ on the morning of February 9. The rainfall that occurred in the third MCS was higher than that of the other two MCSs. For example, accumulated rainfall on February 9, 2015, was higher than the two previous events but not less than 270 mm in Tanjung Priok and Kemayoran (Table 1). The accumulated rainfall levels for the three weather stations during 10:00–13:00 LT were high at more than 100 mm (Figure 3c).

Table 3 shows the characteristics of atmospheric conditions prior to each MCS event using vertical sounding data from Soekarno–Hatta Airport Cengkareng station. The strong convective available potential energy (CAPE) and low convective inhibition (CIN) before the second MCS were 3,688 J/kg and 0.1 J/kg, respectively, yielding a high total precipitable water (TPW) of approximately 62 mm. Although the TPW was strong prior to the second MCS, the rainfall level was lower than the first and third MCSs. This result may be caused by the atmosphere of both the first and third MCSs, which were more unstable than the second MCSs.

The kinematic structure was represented by the vertical profile of wind components. Figure 4 shows the vertical profiles of zonal wind, meridional wind, mixing ratio, and theta-ε in Cengkareng. The zonal and meridional wind, also called wind vector, describes the motion of atmospheric conditions. The mixing ratio and theta-ε were used to describe how systems respond to changes in their environment.

![Figure 3. Time Series of 3 h Rainfall from the Three Weather Stations (Tanjung Priok, Cengkareng, and Kemayoran) during a) January 17, 2013, b) January 17, 2014, and c) February 9, 2015](image)

![Table 3. Properties of Atmospheric Condition Prior to Each MCS Event were Examined using Vertical Sounding Data from Soekarno–Hatta Airport Cengkareng Station. The Convective Parameters for the Three MCSs were Convective Available Potential Energy (CAPE), Convective Inhibition (CIN), and Total Precipitable Water (TPW). Convective Instability Represented the Potential Temperature Difference between 1000 and 700 hPa](table)

| MCS Events | 1     | 2     | 3     |
|------------|-------|-------|-------|
| Date (mm/dd/yyyy) | 01/16/2013 | 01/16/2014 | 02/08/2015 |
| Time (LT) | 1900  | 1900  | 1900  |
| Vertical wind shear (1000 – 700 hPa) | 6.68 m/s | 5.65 m/s | 1.03 m/s |
| CAPE | 2,888.6 | 3,368.4 J/kg | 0 J/kg |
| CIN | 15.2 | 0.1 J/kg | 3.5 J/kg |
| TPW | 58.9 mm | 62.0 mm | 60.3 mm |
| Convective instability | 13.4 K | 12.0 K | 14.4 K |
In Figures 4a and 4b, the wind speed of the third MCS was lowest in the lower levels (~5 and ~3 m/s for zonal and meridional winds, respectively) than in the others, reaching ~12 and ~7 m/s for zonal and meridional winds, respectively. A strong low-level wind speed could assist wind convergence flow and affect the deep convection around GJ. The strong wind speed developed the big MCS prior to the second MCS.

Strong zonal wind occurred in the upper level of the second MCS, followed by the first MCS compared with the third MCS. The strongest zonal wind in the second MCS constructed the cloud shape, and the line shape of the cloud in the second MCS was caused by strong zonal wind (Figure 4). Meanwhile, the lowest zonal wind in the third MCS produced a circular cloud shape above GJ. The lower zonal wind in the second MCS also developed a semi-circular cloud shape.

Figs. 4a and 4b also show that the vertical wind shear in the third MCS decreased compared with those in the first and second MCSs. The strongest vertical wind shear was observed in the second MCS (Table 3). This strong wind shear played a role in building cloud system sizes. Wind shear at the second MCS was higher than that at other MCSs, indicating that the second MCS was wider than the other two MCSs.

In Figure 4c, the water vapor mixing ratio gradually decreased with increasing altitude. The profiles showed good linearity with height. The water vapor mixing ratio of levels above 400 hPa was very small. The water vapor mixing ratio of the second MCS at 700–500 hPa was highest compared with those of the first and third MCSs. At a height of 500–400 hPa, the water vapor mixing ratio prior to the third MCS was highest compared with those of the first and second MCSs. The moist air at 500–400 hPa before the third MCS could contribute to high precipitation above GJ.

The thermodynamic structure represented by the vertical distributions of the theta-e prior to the three MCSs (Figure 4d) showed that the surface level for wet convection was unstable. At 900 hPa, the first and third MCSs exhibited a stable state, and stratification between 900 and 700 hPa was unstable. Meanwhile, the layer was stable from 700 hPa to 400 hPa for all MCSs. At this level, the third MCS was warmest than the first and second MCSs. Precipitation during the third MCS was highest compared with those during the first and second MCSs (Table 1).

The convective cells that produced specific MCSs along time over GJ are shown in Figure 5. Above 200 hPa, easterly winds prevailed throughout the period. However,
in the third MCS, wind direction was semi-northerly. The JRA55 reanalysis data indicated north-westerly winds below 800 hPa over GJ during all MCS events.

Along each MCS, vertical velocity was well diagnosed with alternating positive and negative values before and at mature MCS events. At the low level, positive and negative vertical velocities indicated strong updraft and downdraft, respectively. A strong updraft occurred at the evening of January 16, 2013, whereas a strong downdraft rose in the morning of January 17, 2013, for the first MCS (Figure 5a). An updraft was also observed in the early morning of January 17, 2014 until the evening of February 8, 2015, whereas a downdraft occurred on the morning of January 17, 2014 to February 9, 2015 (Figs. 5b and 5c). These conditions were supported by the strong moist air (relative humidity) at that time. Thus, vertical velocity and relative humidity corresponded to the development and mature phase of MCS.

The reason for the strong updraft of convection over GJ in the evening to early morning is unclear. A reasonable explanation is that rapid radiation loss during the night produces cooler air over the land, so that the boundary layer current enhances the low-level convergence [5]. The low wind convergence plays a role in wind development. Trilaksono et al. [2, 3] reported that an intensive low-level wind convergence and strong low-level vertical shear of wind over the island are created by the northwesterly wind near the surface over the Java Sea. These activities induce local circulation repeatedly, resulting in convection over the northern side of island near the foot of the mountain in the evening.

During the East Asian winter monsoon, mid-latitude circulation directly influences tropical weather through periodical and rapid strengthening of the low-level north-easterlies into the IMC regions following the south-eastward movement of the surface’s high pressure [37, 38]. The complex interaction that causes variability in deep convection is mostly organized by the cold surges and synoptic-scale Borneo vortex. Meanwhile, the MJO influences convection, predominantly on the diurnal cycle and weak synoptic activities [39].

Figure 5. Vertical Cross Sections of Vertical Velocity (hPa s⁻¹, Contour), Relative Humidity (% shaded), and Wind Vectors (m s⁻¹) Averaged Over GJ Along Time a) from 0700 LT (0000 UTC+7) of January 15, 2013, to 0700 LT of January 18, 2013, b) from 0700 LT of January 15, 2014, to 0700 LT of January 18, 2014, and c) from 0700 LT of February 7, 2015, to 0700 LT of February 10, 2015.
Conclusions
The vertical structure of organized convective systems during heavy rainfall over GJ was elaborated. The study analyzed the kinematic and thermodynamic structures of MCS development from mid-January 2013–2014 to early February 2015. Strong low-level winds played a key role in the construction of cloud system sizes. Unstable, low-level moisture convection increased prior to MCS development. Warm, moist air at the altitude of 500–400 hPa contributed to the high rainfall over GJ. The strong low-level convergence winds caused an updraft, which was supported by the high moist air to develop a convective cloud. The high intensity of heavy rainfall that occurred in GJ on the third MCS was due to the third MCS having lower wind flow than the others.

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