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The Properties of Mesoscale Convective Systems in Indonesia Detected Using the Grab 'Em Tag 'Em Graph 'Em (GTG) Algorithm

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Abstract

A mesoscale convective system (MCS) is organized thunderstorms with connected anvils, which has significant impact to the global climate. Focusing on MCS over the Maritime Continent of Indonesia, this study aims to gain a better understanding on the properties of MCSs over the study area. The “Grab 'em Tag 'em Graph 'em” (GTG) tracking algorithm is applied to hourly Multi-functional Transport Satellite-1R (MTSAT-1R) data for two years period to observe the distribution of MCSs and the evolution of MCSs along their lifetime. The result of MCS identification is combined with CloudSat data products to study the vertical structure of the MCSs at various MCS life stages: developing, mature, and dissipating.

The distribution of MCSs in Indonesia has a seasonal variation and distinct diurnal cycle. The life stages of observed MCSs are characterized by distinct cloud microphysics at each stage. In developing stage, the upper level of the MCS raining region shows the presence of precipitating ice particles. As the MCS matures, the proportion of raining area becomes smaller and the intensity of rain is reduced, accompanied by larger occurrence of smaller-sized ice particles at the upper level. In dissipating stage, large hydrometeors no longer exist at the upper part of raining region. Within the MCS anvils, the dissipating stage shows a more uniform distribution of ice-particle effective radius compared to developing and mature stages.

MCS characteristics over the land and ocean are also clarified to differ on the minimum brightness temperature, the equivalent radius, the maximum rain rate, and the rain fraction which vary along MCS evolution.

Keywords mesoscale convective system; GTG tracking algorithm; Indonesia
1. Introduction

A mesoscale convective system (MCS) is organized thunderstorms whose anvils merge into a single mesoscale cirriform cloud shield that usually expands to a linear scale of 100 km (Houze 1993). It has a unique heating profile that consequently affects the surrounding environment of the MCSs, and may affect the Earth’s climate in a larger scale (Houze 1982). The deep convection embedded within the system plays an important role on the vertical moisture transport to the upper atmosphere. MCSs also have been known for their hazardous impacts, such as floods, property damage due to strong winds, and flight accidents.

The MCS frequently occurs over Indonesian region (e.g., Mohr and Zipser 1996). Sohn et al. (2015) found that deep convective clouds (DCCs) over the region have lower visible reflectivity compared to other regions with large occurrence of deep convection, possibly due to smaller ice water content within the oceanic DCC. This indicates regional understanding of MCS is necessary instead of generalizing its characteristics for the whole tropics because different places produce a varying type of cloud system. However, only a limited number of studies have been available in documenting the detailed properties of MCS climatology over the Indonesian region.

The evolution of the MCS microphysics over time is one major interest in the recent times. Previous studies about MCS properties in Indonesia were conducted without considering the life stage of the MCS, particularly when it involved the microphysics of MCS (e.g., Cetrone and Houze 2009; Marzuki et al. 2013). To obtain a complete understanding of MCS over the region, it is of the utmost importance to examine MCS by also taking its evolution into consideration.

For microphysical study of MCS, continuous radar monitoring is preferred. Satellite-based radar data is very useful in the region with limited ground-based radar network such as the Maritime Continent of Indonesia. Yuan et al. (2011) studied the vertical structure of
MCSs using data from the Cloud Profiling Radar (CPR) onboard CloudSat in the A-Train constellation to investigate the microphysics of cloud anvils in MCSs. As the distance from the rain core was used as the proxy of the age of anvil, the study only captured the MCS life stage near the mature stage. The evolution of MCS microphysics can be examined further by combining geostationary infrared satellite and satellite-based radar data (e.g., Imaoka and Nakamura 2012).

The tracking of MCS itself is quite a challenging issue by the fact that MCS may experience merging/splitting during its lifetime. Fiolleau and Roca (2013) developed an MCS tracking algorithm based on three-dimensional image processing approach to tackle the merging/splitting problem. Bouniol et al. (2016) utilized the algorithm and carried out a global study on the evolution of tropical MCS by combining geostationary and low-earth orbiting satellite data. However, their study excluded the analysis of MCSs over the Maritime Continent of Indonesia due to insufficient observation for the MCS tracking algorithm. This study takes advantage of the new “Grab 'em Tag 'em Graph 'em” algorithm (GTG) to track the MCSs (Whitehall et al. 2015), which works well with hourly dataset. Developed based on graph theory, this algorithm enables MCSs to have more than one cloud element to exist at one time frame, thus it is able to handle complex evolution of MCS.

Focusing on MCSs over Indonesian region, this study aims to gain a better understanding on the properties of MCSs at each of their life stages as defined by Houze (1982): developing, mature, and dissipating stages. This study utilizes the CloudSat data products to examine microphysical properties of the MCS, while applying a more direct approach to determine the stage of MCS. Infrared data from the Multi-functional Transport Satellite (MTSAT) is used for tracking the MCS from emergence to dissipation. Combining infrared and CloudSat data will provide another perspective of MCS characteristics at various life stages. The characteristics of MCS over various surface types, comprising land,
sea, and open ocean, are also investigated. Similar to classification by Imaoka and Nakamura (2012), sea region covers any water body within 200 km from the coastal line, while open ocean region lies beyond the 200 km of the coastal line.

2. Data and methods

Previous studies on the evolution of MCS use geostationary infrared satellite imagery to observe MCSs continuously (e.g., Williams and Houze 1987; Boer and Ramanathan 1997). For similar purpose, this study uses brightness temperature (TBB) of channel IR1 (10.8 μm) data from hourly MTSAT-1R, whose coverage includes the study area (15°S – 15°N and 90° – 150°E). The study period spans from January 2007 to December 2008. In this study, MCS is defined as contiguous pixels with TBB less than 240 K with an area of at least 2,400 km², or an area containing TBB difference of at least 10 K, and a lifetime of at least three consecutive frames (three hours). The TBB difference refers to the difference between the maximum (TBB_max) and the minimum (TBB_min) pixel TBB values within an MCS.

The gridded MTSAT-1R data is obtained from Center for Environmental Remote Sensing (CEReS), Chiba University (ftp://mtsat.cr.chiba-u.ac.jp/grid-MTSAT-2.0). The hourly MTSAT-1R data with 0.04°×0.04° resolution is regridded into 0.1°×0.1° resolution for computational efficiency with current version of the MCS tracking algorithm. Rainfall associated with MCS is also examined by using hourly precipitation data from Global Satellite Mapping of Precipitation reanalysis v6 (GSMaP_RNL), which has 0.1°×0.1° resolution. GSMaP_RNL rain rate is derived from combined infrared and passive microwave radiometer data (Ushio et al. 2009). Moreover, monthly precipitation data of Global Precipitation Climatology Project (GPCP) v2.2 provided by NOAA/OAR/ESRL PSD is used to depict rainfall climatology of study area. GPCP data has 2.5°×2.5° resolution and spans from 1979 to the present (Adler et al. 2003).
Considering the first application of GTG for MCS identification in the study area, a sensitivity study was conducted to assess the performance of GTG under various configurations. The result shows GTG is somewhat sensitive to threshold TBB (see Appendix). Using relatively cold threshold TBB requires lower computation costs in terms of time and computational memory, but smaller number of MCS can be identified. Here a warm threshold TBB is desired considering this study aims to investigate the MCS evolution in general, and the warm threshold enables MCS detection with more variable convective strength. The warm threshold is also expected to cover larger area of MCS anvils. Considering this interest, the TBB of 240 K was found to be the optimum threshold for investigating the MCS over the study area. A sensitivity study shows that the minimum TBB distribution within the MCS seems to be more inconsistent for thresholds warmer than 240 K, as indicated by shifting in the distribution peak at different spatial resolutions (see Appendix).

2.1. MCS identification using GTG

An example of MCS detection and tracking using GTG is presented in Fig. 1. The first step is to examine each TBB pixel in each time frame. Connected pixels with TBB less than 240 K with area at least 2,400 km², or with smaller area but has convective fraction (TBB_{min}/TBB_{max}) less than 0.9, are collected and considered as cloud elements (CEs). Percentage overlaps between CEs in two consecutive time frames are calculated, in which the smaller area is used as the denominator. Graphs are constructed with CEs as the nodes and overlapping percentages as the graph edges (colored lines in Fig.1b). A graph, here considered as a cloud cluster (CC; Fig. 1b), is a collection of CEs connected through edges with overlapping percentage exceeding 90% or with overlapped-area over 10,000 km². Weights are given to the graph edges based on the overlapping portion: larger overlapping for smaller weights. The detailed weights are: one for more than 95%
overlapping percentage; two for overlapping percentage between 90% and 95%; and three
for 10,000 km² overlapped-area. No edge is built when the overlapping percentage is
below 90%, thus a new graph will be constructed instead, with the newest CE as the
starter.

It should be noted that, although GTG also includes small CEs with areas less than
2,400 km², some small MCSs might not be detected because the TBB data is regridded to
a relatively coarse resolution. The high overlapping percentage criterion (90%) in GTG
also makes the detection of small systems becomes more difficult.

After all CCs are identified, GTG eliminates CCs with lifetime less than 3 frames and
performs the deepest Dijkstra shortest path method (Dijkstra 1959) to determine the core
evolution of the CC, i.e., the MCS (Fig. 1c). The deepest here refers to the process of
choosing the route that leads to the farthest evolution of the CC. The shortness of a path is
determined by the total weight of a route, where a short path can also mean a simple path
(or path with minimum weight).

In this example, the CC (Fig. 1b) experiences a complex evolution involving several
merging/splitting events. The graph shows that the farthest evolution of cloud element
“F10CE1” is the cloud element “F31CE5” at frame 31. By implementing the deepest
criterion, the algorithm will choose the route that leads to this particular CE. There are
several possibilities of routes to reach the last CE “F31CE5”, but the shortest criterion
restricts the selection of routes to the route with minimum cost, or in other words, the
branch with the simplest evolution. Consequently, the route involving “F15CE2” and
“F17CE14” is chosen as the main core of the “F1CE1” evolution (MCS 1 in Fig. 1c). The
other “complex” branches are then categorized as different systems, as in the case of
“F15CE15” and “F17CE1” (MCS 2 and MCS 3, respectively). In the process, if the end of
the CC has not been reached, the algorithm simplifies the graph by discarding any CEs
without continuation (childless nodes), making some CEs in Fig. 1b, such as “F24CE4”
and “F22CE5”, excluded from the final graph (Fig. 1c). In the end, three MCSs are identified after the deepest Dijkstra shortest path is applied to the initial graph of CC.

Figure 1b shows that the cloud element “F19CE6” is the merging product of two different systems: one starts from “F10CE1” and the other starts from “F15CE9”. The original area-overlapping technique (Williams and Houze 1987) will require one of the system to be terminated immediately, ending the system’s life unnecessarily, because it is unable to handle multiple CEs at the same time. GTG considers both systems as one MCS without any need to eliminate one of the systems. It is just that the MCS consists of two CEs from frame 15 to 18, as shown in Fig. 1c (MCS 1).

Some splitting events can be found in the graph, for example in the frame 14-15 and 16-17, creating new systems starting from “F15CE15” and “F17CE1”, respectively. Nevertheless, these two systems can be considered to split physically as they separated themselves from the main evolution of “F10CE1”. They moved to different direction, as suggested by no relation with the main route (no connecting edge) was ever found at latter time frames.

To better understand how GTG works, an example of MCS segmentation by GTG for the case at the Bay of Bengal on 10 - 11 November 2011 is shown in Fig. 2. The result of GTG is compared with Fig. 10 of Fiolleau and Roca (2013; hereafter FR13), who developed an algorithm named TOOCAN. GTG was run using a threshold TBB of 235 K and an area criterion of 1,200 km² to match the configuration in FR13. FR13 used METEOSAT-7 data every 30 min. with 5 km resolution, but GTG here used hourly MTSAT-2 data with a spatial resolution of 0.04°×0.04°. The original area-overlapping technique (Williams and Houze 1987) identified two separate systems at 2130 UTC on 10 November 2011, but the MCSs became one at 0000 UTC the next day (Fig. 10 right in FR13). Since the two systems were merged together to build a larger MCS at 0000 UTC, GTG treated those two systems as the same MCS from 2130 UTC (Fig. 2), avoiding the unphysical
dissipation of MCS #2 due to merging in the original area-overlapping technique. TOOCAN could identify the individual convective cells (Fig. 10 middle in FR13) within the large-scale MCS, thus it could maintain each system consistently. The large MCS in this case was clearly dissipating from 0030 to 1130 UTC on 11 November 2011. The area overlapping technique by Williams and Houze (1987) detected many new MCS at 1130 UTC as the large cloud elements at 0900/0930 UTC separated into smaller fractions (i.e., new MCS artifact). Although TOOCAN detected multiple small systems while GTG identified them as one system, both TOOCAN and GTG were able to portray the dissipation of the large MCS as they produced no new MCS at 1130 UTC.

From the comparison described above, we conclude that the results of GTG and TOOCAN are comparable, in which GTG seems to capture the general feature of the MCS, while TOOCAN captures the individual cores in detail. Due to the nature of the algorithm, TOOCAN requires high temporal resolution data and we believe that it requires more extensive computer resources, making GTG a preferable option for the present study.

2.2. Life stage identification

After detection and tracking step, the life stage of MCSs is determined based on the evolution of size and minimum TBB of the MCSs regardless whether merging and splitting events exist during the MCS lifetime (Fig. 3). The minimum TBB refers to the smallest pixel value of TBB. If there are more than one CEs building the MCS at a particular time, the minimum TBB is then the coldest pixel value from all available CEs of the MCS at the same time level, while the size of MCS is the summation of these CEs. For simplification, the size of MCS is represented as equivalent radius, which is the radius owned by the MCS at a given time under the assumption that the cirrus shield has a perfect circle shape with the same area. Adapting the method from Futyan and Del Genio (2007), a maximum of sixth order polynomial fitting on equivalent radius and minimum TBB for smoothing is
applied to the systems with lifetime duration longer than 6 hours, and lower order on the systems with shorter lifetime duration. The best order polynomial fitting is determined based on F-test result (Takahashi and Luo 2014).

The system is assumed to have an idealized development as described in Houze (1982): it develops vertically first, expands horizontally later, and disappears as it dissipates. Developing stage is defined as the period before the minimum TBB within the MCS falls to its lowest (period 1 in Fig. 3). The period after the system reaches its maximum size is defined as dissipating stage (period 3). The mature stage of the system is located between the points when the system reaches its lowest minimum TBB and the system reaches its maximum size (period 2). In reality, the evolution of an MCS can be very complex that there is no clear peak of size and minimum TBB, making it difficult to determine a robust life stage. Therefore, only MCSs with successful life stage identification are accounted in microphysical analysis. Here the identification of MCS life stage is considered successful only if its evolution of size and minimum TBB follows the aforementioned criteria, thus the life stages can be clearly discerned.

We made a slight modification to the method to accommodate any strengthening system that has a clear local minimum of size. The stage of the system is determined based on the above criteria after dividing the lifetime into two periods, with the point of local minimum as the separator.

2.3. Microphysical analysis

The analysis of MCS microphysics in this study employs CloudSat data products from CloudSat Data Processing Center, Colorado State University. The products used comprise radar reflectivity factor from 2B-GEOPROF R04 (Marchand et al. 2008), cloud mask from 2B-GEOPROF-LIDAR R04 (Mace and Zhang 2014), and ice properties from 2C-ICE R04 (Deng et al. 2010, 2013) data. CloudSat footprints that collocate with MCSs are assigned
to a particular life stage of the system, similar to Takahashi and Luo (2014). Afterwards, CloudSat profiles with similar life stage are combined to create the composite images at the corresponding stage. The summary of layer base and layer top within a column in 2B-GEOPROF-LIDAR is used to separate deep convective (cloud base height/CBH < 3 km and cloud top height/CTH ≥ 10 km) and anvil (CBH ≥ 3 km and cloud top height ≥ 10 km) parts within the MCS. The presence of rain within a CloudSat profile is determined solely from radar reflectivity as described in Yuan and Houze (2010). The profile is considered raining if its maximum reflectivity between 1 and 2 km above the surface is >-10 dBZ, or, if the maximum reflectivity in the three adjacent bins including the earth’s surface is <25 dBZ.

The 2C-ICE product combines the radar profiles of CloudSat and the lidar profiles of Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) to estimate ice microphysical properties (Deng et al. 2010). For the mixed phase region or in the optically thick clouds where the lidar is usually attenuated and unavailable, the 2C-ICE uses an empirical relationship using the radar reflectivity factor and temperature. The 2C-ICE also accounts Mie scattering in the radar forward model lookup table. It should be noted that the retrievals of IWC and \( R_e \) may suffer from some degree of uncertainties, mainly owing to the uncertainty in the shape of ice particles. Deng et al. (2013) estimated the uncertainty in IWC retrievals of 2C-ICE product to reach 30%.

3. Results and discussions

The occurrence of MCSs in Indonesia during the study period is 17619, with 86% of the systems having successful life stage identification. Figure 4 shows the properties of MCS during the two years period, comprising the lifetime duration (Fig. 4a), the maximum equivalent radius (Fig. 4b), and the minimum TBB reached by MCS during its lifetime (Fig. 4c). The majority of MCSs in Indonesia is short-lived systems, persisting for about less
than 14 hours with a peak at around 4–6 hours. Most of the MCSs expands to an equivalent radius of around 100 km. According to a study of cloud-top height estimation by Hamada and Nishi (2010; their Fig. 3), the minimum TBB distribution with almost no occurrence over 220 K suggests almost all MCSs in Indonesia grow to an altitude of approximately 14 km at least, and the peak at 200 K indicates many MCSs grow up to 16 km altitude.

3.1. Spatial distribution

The MCSs, represented by blue circles with red outline in Figs. 5a and 5b, are mostly formed along the coastline. During daytime, sea-breeze converges to the center of the island and strengthens the inland convection, creating a favorable condition for MCS formation over land. MCS formation is more concentrated over the sea during nighttime, as the land-breeze from the surrounding islands converges to some straits (Qian 2008).

More details on the diurnal variation of MCS occurrence can be investigated further using MCS classification based on the surface type shown in Fig. 5c. The gray color denotes land surface, while cyan color for sea (within 200 km from the coastal line) and white for open ocean area (beyond the 200 km of the coastal line). The MCS is categorized as a particular type if its centroid is located over a similar surface throughout its entire lifetime. The hourly distribution of MCS occurrence (first detection at developing stage) for each surface type is presented in Fig. 5d. The time of occurrence is denoted in local time (LST), which is calculated based on the longitude of the MCS centroid. For example, the local times for two MCSs with centroid at 90° and 135°E, both occurring at 0000 UTC, are 6 and 9 LST, respectively. The land-type MCS has a clear diurnal pattern, with a robust peak in the afternoon around 14 LST. The sea-type MCS shows two peaks at midnight (1 LST) and afternoon (13 LST). The diurnal variation for sea-type MCS is weaker than the land-type MCS because of weaker diurnal variation of surface heating.
Meanwhile, there is no clear peak for the open ocean-type MCS owing to very weak diurnal variation on surface heating and the absence of land influence over the open ocean area. The MCS in Indonesia varies in spatial distribution according to different atmospheric conditions in different seasons. In December-January-February (DJF), the MCS occurrence is high across the whole region correlating with the movement of the Wet Monsoon from the north (Fig. 6a). In contrast, the distribution is generally sparser in June-July-August (JJA) with almost no MCSs forming over the southern part of Indonesia because most of Indonesia regions are affected by dry Australian monsoon (Fig. 6b). The occurrence MCS over the Pacific Ocean does not change significantly owing to abundant moisture over the open ocean area. The summary of MCS latitudinal distribution in Fig. 6c suggests high MCS concentration is located over the hemisphere where the ITCZ resides. However, maximum occurrence of MCS persists at around 2°S regardless of the season, possibly due to the richest land-sea distribution and more complex topography over Indonesia at this latitude.

The seasonal variation of MCS occurrence along with its physical properties in several major islands in Indonesia, comprising Sumatra, Java, Borneo, Sulawesi, and Papua, are shown in Fig. 7. The locations of those islands can be seen inside the red boxes of Fig. 5c. In general, the seasonal variations of MCS properties are in accordance with seasonal rainfall (Fig. 7 bottom). The amplitude of seasonal variation varies regionally. The following points discuss the regional variability of the frequency of MCS occurrence, MCS size, minimum TBB within the MCS, and MCS lifetime in more detail.

a. The frequency of MCS occurrence

Fig. 7 (first row) shows average number of MCS occurrence in each month in five different sub-regions. Because of the dependency on total area of each region, the annual
mean and standard deviation of frequency are adjusted by normalizing them with the area of each corresponding region (values inside the brackets). Sulawesi has the most concentrated MCS with a frequency value of 1.5 month$^{-1}$ (10,000 km$^2$)$^{-1}$. It is followed by Papua (1.4), Borneo (1.3), Sumatra (1.0), and Java (0.9), respectively. The small value of mean frequency in Java may be attributed to the strong suppression of MCS development during the dry monsoon season in JJAS. Java shows the highest seasonal variation, as shown by the highest standard deviation of 0.6. The second largest seasonal variation appears in Sulawesi (0.5), whereas the other regions show relatively weaker seasonal variation (Sumatra, Borneo, and Papua). MCS in Sulawesi has high annual mean frequency although it shows rather strong seasonal variation. High concentration of MCS in this region is likely due to its unique surface inhomogeneity (Fig. 5c). Sulawesi has many large bays and straits with narrow land mass, all of which favor air convergence from the adjacent sea/land during the daytime/nighttime and hence amplify the diurnal cycle.

b. MCS size

Fig. 7 (second row) shows the distribution of equivalent radius in the five sub-regions. Annually, Borneo exhibits the largest MCS with average equivalent radius of 150.8 km, followed by Sumatra (149.8 km), Papua (136.9 km), Sulawesi (128.2 km), and Java (122.8 km). Seasonal variation of MCS size is very clear in Java. The average value of MCS equivalent radius is less than 100 km in dry season, but it can reach 150 km during the wet season. Seasonal variation in Sulawesi is the second largest, while Borneo, Papua, and Sumatra have relatively weak variation of MCS size.

c. Minimum TBB

The minimum TBB is often related with the maximum strength of convective cores within the MCS. The regional difference in the annual mean of minimum TBB is not large
between the five sub-regions (Fig. 7 third row). The coldest minimum TBB is found in Papua (197.5 K) and the warmest is found in Sumatra (200.6 K). The minimum TBB also shows seasonal variation. Drier months tend to coincide with warmer minimum TBB and wetter months tend to coincide with colder minimum TBB. The strongest seasonal variation on minimum TBB within the MCS is shown in Java and Sulawesi (2.3 K).

d. Lifetime

Borneo exhibits the longest lifetime of MCS with an average of 9.6 hours (Fig. 7 fourth row). It is followed by Papua (8.8 hours), Sulawesi (8.5 hours), and Sumatra (8.3 hours). The shortest-lived MCS is in Java (7.4 hours). The long-lived MCS prevails in all months in Borneo (weak seasonal variation). Meanwhile, Java exhibits strong seasonal variation of MCS lifetime.

3.2. Land and ocean differences

Besides the frequency of occurrence, the MCS over Indonesian region also shows diurnal variation of size. Figure 8a shows the hourly variation of mean MCS size for land-MCS (red color) and the combined sea- and open ocean-type MCS (blue color). Hereafter, the combination of sea- and open ocean-type MCS is referred as oceanic-MCS. To explain the variation in the MCS size, the occurrence frequency of three MCS life stages over land and oceanic surfaces are presented in Figs. 8b and 8c, respectively.

Chen and Houze (1997) documented diurnal variation of the size of deep convective systems over the western Pacific and Maritime Continent. They separated cloud areas into three threshold TBBs (< 208 K, 235-208 K, and 260-235K) and calculated their fractional coverage. Over the land, the fractional area with cold TBB (< 208 K) reached a peak in the afternoon, followed by a peak of moderate TBB (235-208 K), and a peak of warm TBB (260-235 K) in the midnight. The phase lag between the area fractions indicates different
stages in the life cycle of deep convective systems. Successive warmer cloud top peaks represents weakening stage of life cycle. The minima of fractional areas were observed at noon. On the other hand, fractional areas over the ocean were found to have maximum peak of cold TBB in the dawn/morning, while the peaks of moderate TBB and warm TBB appeared in the afternoon. Amplitude of diurnal cycle in land was much greater than in the ocean.

Figure 8a shows that a robust minimum peak of MCS size for land-MCS is reached around 14 LST. At this time, the developing stage is dominant thus the anvil of MCS is yet to grow which results in minimum area. Following this time, the size is growing fast until a certain time at the peak of mature stage around 17 LST. The MCS size is somewhat steady and slightly growing until after midnight. This pattern of MCS size variation over land is generally consistent with Chen and Houze (1997) for their warm threshold TBB.

Over the oceanic surface (sea and open ocean), the diurnal cycle exists but with weaker amplitude compared to the land surface (Fig. 8a). In contrast to the land-MCS, the minimum area of oceanic-MCS occurs at the midnight and the maximum area occurs in the afternoon. This pattern is also consistent with Chen and Houze (1997) for the oceanic systems using warm threshold TBB. Although the variation of life stage over the oceanic surface is not as robust as over the land, a peak of developing stage after the midnight can be observed, which is followed by the mature and developing stages (Fig. 8c).

Figure 9 shows the composite evolution of the MCS over Indonesian region. The solid line denotes the evolution of land-MCS, while the dashed line shows that of oceanic-MCS. Each life stage is normalized into three time steps, making a complete MCS lifetime consists of nine steps. The values at the first and third steps of each stage represent the values at the beginning and the end of the corresponding stage, respectively, while the value at the second step represents the midpoint value of the corresponding stage. If the stage duration is an even number, the value at the second step is obtained by linear
interpolation from the nearest two points (e.g., hour-2 and 3 for a stage duration of 4 hours). The evolution of minimum TBB in Fig. 9a suggests the cloud top height of land-MCS is higher at developing and mature stages, but becomes comparably low to oceanic-type at dissipating stage. The land-MCS shows somewhat smaller spatial extent compared to oceanic-MCS (Fig. 9b). The maximum rainfall, here defined as the largest pixel value of rainfall rate within the MCS, occurs at the time the MCS reach the smallest minimum TBB, with more intense rain for land-MCS (Fig. 9c). Both land- and oceanic-MCS show increasing raining area in developing stage, followed by decreasing raining area to the end of MCS lifetime, although the fraction is somewhat larger for oceanic-MCS (Fig. 9d). The difference found between land- and oceanic-MCS is particularly visible in developing and mature stages, indicating faster changes of convection over the land compared to the sea due to stronger diurnal cycle inhibited by the land area. Consequently, although the development of land- and oceanic-MCS differs at the beginning, both types show similar characteristics at the end of their lifetime as the dominant convections of the MCS vanish.

3.3. Microphysical properties

Figures 10 and 11 show the normalized contoured frequency by altitude diagram (CFAD; Yuter and Houze 1995) of radar reflectivity, ice-particle effective radius ($R_e$) and ice water content (IWC) associated with MCS at various life stages for the deep-convective raining region and the anvil part, respectively. We use CFADs in this study to gain further insight into the vertical distribution of hydrometeors and possible microphysical processes within the MCS. The CFADs are constructed by compositing the profiles of all MCSs over land, sea, and ocean, without any separation on the surface type. The frequency shown is normalized by the bin of maximum frequency for each stage. The total number of overpassed MCS within two years period is given for each MCS life stage (nmcs). There are differences in this number due to the sampling of A-train constellation that only
overpass the region every 13:30 and 01:30 LST. Considering developing stage has shorter
duration while the maximum initiation of MCS occurs in the late afternoon, the number of
developing MCS captured by CloudSat is much fewer than mature and dissipating stages.
The number of corresponding CloudSat profile to build the CFAD is also given as nprof.

The melting layer is visible in the CFAD of radar reflectivity within the raining region for
all stages at around 5 km altitude (Fig. 10). Although multiple scattering effect may
influence the radar reflectivity below the melting layer (Battaglia et al. 2007), the
decreasing trend toward the surface is visible in all stages owing to attenuation by
precipitating particles. The mode of reflectivity is distinctive among the three stages. The
developing stage has the mode of large reflectivity at high altitude, extending from 6 to 11
km altitude. This mode becomes moderate in mature stage and becomes very weak at
dissipating stage. According to Luo et al. (2014), the mode of reflectivity at developing
stage indicates the presence of large size and/or large concentration of ice particles in
upper levels associated with the strong updraft. The updraft becomes weaker as the MCS
matures, thus dissipating stage consists only smaller particles at the upper levels. The
differences of radar reflectivity CFAD between stages are presented in Fig. 12. The radar
signal below the melting layer (around 5 km) of the developing stage gives higher
frequency below 0 dBZ compared to the latter stages, denoted by blue color in the
difference of mature-developing and dissipating-mature stages, indicating that the
developing stage experiences more severe attenuation due to heavier rainfall. This result
is consistent with the finding by Kondo et al. (2006), who reported the occurrence of
intense rainfall at the beginning of isolated convective system’s lifetime. Looking at the ice
portion of the cloud, the developing stage has large $R_e$ and IWC compared to the mature
and dissipating stages at the same altitude, particularly above 8 km (Fig. 10 middle and
bottom rows). At developing stage, strong updrafts bring large ice particles to upper levels
and create favorable condition for particle growth by collection. The mode of IWC of the
developing stage has similar value extending from around 7 to 12 km, but a gradual
decrease by increasing height is observed for the particle size. This indicates larger
number concentration of ice at the upper parts, but smaller concentration below. One
mechanism proposed for this finding is that large amounts of smaller particles have formed
larger particles, yielding smaller concentration of ice particles at middle level. Towards the
dissipating stage, most of large particles have fallen or dissipate because of the weakened
updraft, whereas the small particles are able to stay afloat in the MCS. These yield in an
increasing concentration of smaller \( R_e \) and smaller IWC during the late stage of MCS as
shown in Fig. 10. The smaller \( R_e \) at dissipating stage can also be attributed to the
decreasing convective rain fraction towards the end of the convective system’s lifetime as
shown by Kondo et al. (2006).

The reflectivity of the non-raining anvils increases with decreasing height, implying
larger concentration and/or larger size of ice particles at the lower levels (Fig. 11 top). The
differences of radar reflectivity CFAD in Fig. 12 between stages suggest that the anvils in
developing stage is quite similar to those in mature stage (Fig. 12 bottom-left). Compared
to dissipating stage, the anvils in developing and mature stages have more occurrence of
both small and large reflectivity at any altitude (Fig. 12 bottom). Yuan et al. (2011)
regarded MCS anvils near the rain core as young anvils. They found these young anvils to
have broader distribution of reflectivity compared to the ones located far away from the
raining area (old anvils), which is consistent with our results when comparing the anvils in
developing-mature stages (associated with younger anvils) and dissipating stage
(associated with older anvils).

The reason of broader reflectivity in earlier stages within the MCS anvils can be
examined further by considering the profile of \( R_e \) and IWC (Fig. 11 middle and bottom
rows). The distribution of \( R_e \) is similar among all stages, thus the difference in IWC may
have larger contribution to the difference in radar reflectivity profile within the anvils in
different stages. However, the dissipating stage seems to have more uniform size compared to the developing and mature stages, especially below the altitude of 13 km, as shown by narrow mode in red color. The anvils in developing and mature stages show the signature of large IWC at high altitude around 10 km, but the anvils in dissipating stage show less occurrence of this large IWC at the same altitude. One reason for these findings is the anvils at the earlier stages consist of large amount of particles including both the small and large ones, which are detrained from the convective cores. As the large particles can only remain in the atmosphere for a relatively short time, they gradually fall down and are likely evaporated at lower level, thus only small amount of particles remain aloft as suggested by decreasing appearance of large IWC as the MCS progresses to dissipating stage. After some time, the remaining smaller particles grow by vapor deposition, yielding less variation in the ice particle size at the dissipating stage that results in narrow distribution of Re.

4. Conclusions and recommendations

The properties of MCS over the Maritime Continent of Indonesia have been documented for the two years period of 2007–2008. The variability of MCS distribution and its properties at different life stages can be revealed by utilizing the GTG tracking algorithm. The MCS occurrence has clear seasonal variations, which are influenced by monsoonal flow changes. MCSs are concentrated over land around daytime, but over the sea area around nighttime. The MCSs existing over the various surfaces demonstrate different physical properties. The most striking of these differences are the land-MCSs reach lower minimum TBB, with larger size and more intense rainfall compared to oceanic-MCSs. Those differences are the most distinguishable around the end of developing stage to the end of mature stage.
Within the raining region, the developing stage has the dominant mode of large reflectivity at high altitude, with smaller reflectivity below the melting layer. The mode at high altitude gradually weakens as the MCS dissipates. The ice portion of raining region in developing stage indicates large particles have already grown from numerous smaller particles, resulting in relatively small ice concentration at the middle level. During dissipating stage, the particles tend to concentrate at the middle level, possibly due to the existence of particles with slow fall speed.

The radar reflectivity of MCS anvils in developing stage is very similar to mature stage, with a broader distribution than dissipating stage. The broader distribution of ice effective radius in developing stage is likely due to large supply of both small and large particles from the convective core. The anvils in dissipating stage have more uniform particle size with lower occurrence of small particles compared to those in the previous stages.

Overall, we have presented some differences of MCS properties in the sub-regions of Indonesia, where Java exhibit the strongest seasonal variation among the five sub-regions. Further studies are required to explore more detailed characteristics of MCS specific to each sub-region. Although we provide the regional feature of MCS microphysics for Indonesian region in general, the difference in microphysical properties of each sub-region is yet to be unveiled comprehensively in the current study and should be clarified in the future.

The hourly GSMaP_RNL data provides a useful estimate of rainfall evolution within the MCS. However, it may have some dependency on TBB due to the nature of the rain rate retrieval algorithm. In the future, a study using rainfall dataset that has high temporal and spatial resolutions with less dependency to TBB may be able to reveal a more detailed evolution of rain within the MCS.

Future study involving application of GTG on high frequency observation on the study area by Himawari-8 may be worth investigating considering convective core within the
MCS may experience rapid changes within a short time period. Moreover, the high spatial resolution of Himawari-8 can facilitate further studies of MCS over the sub-region of Indonesia. Improvement on GTG algorithm is also still possible to obtain better representation of MCS.

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Appendix

Sensitivity study of GTG

We performed a sensitivity study to investigate how different configurations influence the results of GTG. More specific objective is to give an appropriate threshold for MCS detection over the study area. The sensitivity experiment covers the evaluation of input data spatial resolution and threshold TBB. The threshold TBB should be warm enough to covers anvil and earlier/latter stage of the MCS.

Four days run (96 hours) of MCS tracking over the study area (15°S – 15°N and 90° – 150°E) was performed at the beginning of each month for the season of March-April-May 2007. We tried running GTG using input at two different spatial resolutions: 0.04°×0.04° (S04), which is the original resolution of gridded MTSAT-1R data; and 0.1°×0.1° (S10), which is obtained by regridding the same dataset using bilinear interpolation method. Several thresholds TBBs for delineating cloud elements are applied on GTG, ranging from
213 K to 253 K. Other criteria for MCS (area and minimum lifetime) are basically the same as described in Subsection 2.1.

The results of sensitivity study show that the computation time increases for increasing threshold TBB (Fig. A1). This happens because there are more cloud elements being isolated for warmer thresholds compared to the colder ones, and the complexity of the graph is higher for warmer thresholds. When comparing the two spatial resolutions, experiments with S04 requires much longer duration than S10 because of the numerous pixels involved in S04. The increasing duration is more drastic in S04 than in S10, but both configurations yield similar results as shown by similar statistics of the MCSs found (Fig. A2). Therefore, for computational efficiency, GTG is applied on MTSAT-1R data that has been regridded to 0.1°×0.1° resolution in our main analysis.

Using warmer threshold TBB is expected to give larger number of cloud elements (CEs) since cloud development may happen with different strength, yielding variable cloud top height indicated by variable TBB values. Figure A3a, indeed, shows that the number of edges (i.e., CEs) associated with MCS for warmer thresholds is larger than the one for the colder thresholds. However, if the TBB threshold is too warm as in 253 K experiment, the number of CE becomes small again because several CEs defined by colder thresholds may be detected as one CE in the experiment with warmer thresholds.

The number of MCS found increases steadily from 213 K to 225 K, fluctuates a little bit from 225 K to 245 K, and start decreasing afterwards as shown by Fig. A3b. This indicates the number of MCS found does not show linear relationship with threshold TBB used, particularly for the warmer thresholds (225 to 253 K). The warm end for optimum MCS detection over the study area seems to be 245 K. Similar to 215 K experiment, the number of MCS found for 253 K thresholds is considerably lower than the other warmer thresholds, although the similarity came from different reason. The experiment with 215 K threshold has small number of MCS due to infrequent occurrence of contiguous 215 K pixels that
satisfy the CE criteria, while the 253 K threshold yields small number of MCS due to large
number of CEs being categorized as the same system (Fig. A3c). In other words, one
MCS of 253 K may consist of a lot of cloud elements during one time frame yielding MCS
with larger size, or the cloud elements are connected to each other for a very long time
yielding a longer-lived MCS compared to the other thresholds.

Very warm threshold TBB may not give a false depiction of MCS, but it rather identifies
the feature in a larger scale. This indicates the necessity of applying additional criteria
when using a very warm TBB threshold in GTG when examining MCS in detail, either in
the process when it determines which cloud elements belong to which MCS or the
delineation of the CE at the beginning.

The proportion of MCS with successful life stage identification (see Subsection 2.2)
tends to be higher for colder thresholds (Fig. A3d). The complexity of the graph is
increasing for warmer threshold as indicated by larger number of cloud elements within
one MCS, thus the MCSs experience more complex evolution compared to the MCS
delineated by colder thresholds. However, all TBB thresholds give more than 80% of the
population as having successful life stage identification.

Although the warm end of TBB threshold seems to be around 245 K, a value 240 K is
chosen as the TBB threshold for the main analysis. The minimum TBB distribution within
the MCS seems to be more inconsistent when using thresholds warmer than 240 K for
different spatial resolution, as indicated by shifting in the distribution peak (Fig. A2c).

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