1. Introduction

The launching of the Himawari-8 satellite in October 2014 creates the possibility of more detailed cloud monitoring, especially in the region of Indonesia, where a high-frequency observation covering the whole area was not available before. Himawari-8 carries the Advanced Himawari Imager (AHI) that captures radiance at 16 spectral bands with improved spatial and temporal resolutions compared to those of its predecessor, the Multi-functional Transport Satellite 2 (MTSAT-2) imager (Bessho et al. 2016). With the interval of 10 min for the full disk scans and 2.5 min for the specific target areas, AHI data is suitable for studying the evolution of convective clouds, which can develop in a relatively short period of time. The region of Indonesia is one major region with a large occurrence of mesoscale convective system (MCS) throughout the year, although the location of the most concentrated area differs from season to season (Mohr and Zipser 1996; Putri et al. 2017). Putri et al. (2017) studied the statistical properties of MCSs occurring over the Indonesian region by applying the “Grab ‘em Tag ‘em Graph ‘em” (GTG) tracking algorithm (Whitehall et al. 2015) to the hourly MTSAT-1R infrared data regridded to a 0.1° × 0.1° spatial resolution. Developed on the basis of graph theory, the GTG algorithm enables the MCSs to have multiple cloud elements (CEs) at one time frame simultaneously; thus, it can handle the complex evolution of the

NOTES AND CORRESPONDENCE

Evolution of Mesoscale Convective System Properties as Derived from Himawari-8 High Resolution Data Analyses

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Abstract

Two case studies of the mesoscale convective system (MCS) in the Indonesian region were conducted by applying an improved “Grab ‘em Tag ‘em Graph ‘em” (GTG) tracking algorithm and the Integrated Cloud Analysis System (ICAS) algorithm to Himawari-8 AHI infrared data. The first case over Java Island showed a land-originating MCS in the boreal winter, which coincided with a wet phase of Madden-Julian Oscillation (MJO) over the Maritime Continent. The second case showed the evolution of MCS under the influence of a strong vertical wind shear during the boreal summer. The cloud top height (CTH) of deep convective part in the first case was larger than that in the second case, while the temporal evolution of CTH was similar between the two cases. For the anvil part, the median CTH of the second case was relatively stable at around 13 km, while that of the first case showed a considerable temporal variation ranging from 14 to 16 km. The cloud-particle effective radius (CER) of the anvil increased after the period of maximum deep convective CTH in both cases, although the CER was slightly larger in the second case than in the first case. These differences in cloud properties between the two cases were attributable to the background wind profiles.

Keywords  “Grab ‘em Tag ‘em Graph ‘em” tracking algorithm; infrared channels; mesoscale convective system

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MCSs. Because of this ability, GTG has the advantage of studying the MCSs in Indonesia, where the merging of multiple convective cells is present in the MCS lifetime.

In the present study, we will demonstrate the application of the GTG algorithm to the frequent observation of AHI data to study the temporal evolution of the MCS properties in detail, given that now the data are available every 10 min. The algorithm of GTG was modified to increase its applicability to the high resolution infrared data (Section 3) and then applied for investigating two case studies of MCSs in Indonesia. The first case showed the MCSs formed over the Java Island, which is known as the most densely populated region in Indonesia. The occurrence of torrential, heavy rain associated with the MCSs have been known for causing floods in this region repeatedly (e.g., Wu et al. 2007, 2013), including one on February 6 and 7, 2016. The second case covered an MCS that formed offshore of the western Sumatra Island during a dry season when a strong vertical wind shear prevailed on August 25 and 26, 2015.

To complement the analysis in Putri et al. (2017), here we employed the Integrated Cloud Analysis System (ICAS; Iwabuchi et al. 2016, 2018) to retrieve the properties of the MCSs, such as cloud top height (CTH), cloud optical thickness (COT), and cloud-particle effective radius (CER) from multi-bands of AHI data rather than using a rough approximation of particle effective radius (CER) from multi-bands of (CTH), cloud optical thickness (COT), and cloud-particle effective radius (CER) estimations may arise if vertical inhomogeneity exists, such as under the presence of multi-layer clouds with overlying thin cirrus. Large COT tends to be underestimated, and the CER of optically thick cloud (COT > 5) tends to have large uncertainties because the infrared measurement loses sensitivity in the lower part of cloud. Despite these limitations, ICAS still provides useful estimates for studying the evolution of MCS properties over the Indonesian region. More detailed description on the ICAS method for AHI data can be found in Iwabuchi et al. (2018).

In addition to the data from AHI observations and other input data for ICAS, we used the meteorological data of the Japanese 55-year Reanalysis (JRA-55; Kobayashi et al. 2015) data set to investigate meteorological fields around the MCSs over the study area. The JRA-55 data set spans January 1958 to the present and is available every 6 h with a horizontal resolution of 1.25° × 1.25° and 37 vertical pressure levels.

3. Improvement of GTG tracking algorithm

MCS tracking by using GTG is started with the identification of CEs, i.e., areas with TBB less than a particular threshold, from each frame of satellite imagery. The overlapping fractions between CEs in two consecutive frames are calculated to construct an initial graph, or cloud cluster (CC). The CEs act as the graph nodes connected by weighted edges according to the overlapping fraction: larger weight for smaller overlapping fractions. The CEs that belong to the same CC are connected to each other with an overlapping percentage exceeding 90 % or an overlapped-area over 10,000 km². An MCS is defined as the core evolution of the CC and obtained by applying the deepest Dijkstra shortest path method (Dijkstra 1959) to the initial graph. The algorithm chooses the route that leads to the farthest evolution of the CC (deepest) with the simplest path, or quantitatively, the smallest total weight (shortest), as the evolution of the main MCS. Multiple MCSs may exist in a single initial graph of CC, particularly if the CC experiences a complex evolution that splits and subsequently merges, creating an independent system propagating differently from the main system. In this case, the starting point of a branch (and its child nodes) after a split is identified as a separate MCS. Here since MCSs are documented as graphs, the MCSs can have more than one CE simultaneously at one time frame, allow-
ing a more accurate depiction of the MCSs, especially when several individual convective cells merge to form a larger system. The principles of the original GTG are described and illustrated in more detail by Whitehall et al. (2015) and Putri et al. (2017).

As explained above, the original GTG algorithm uses a fixed, single TBB threshold to identify the CEs that build the MCSs. However, our preliminary study using AHI infrared data revealed a high possibility of connected individual CEs with a very large area when using a simple threshold method to delineate the CEs owing to the high spatial resolution of AHI data. Consequently, a larger system was identified instead of the specific MCS of interest, since the large CEs were categorized as the same MCS (Figs. 1b, e). Separating a large CE consisting of several convective cores into multiple smaller CEs by only using a simple threshold method is quite difficult unless the threshold TBB is changed to a colder value. Nevertheless, this study prefers the warm threshold of 240 K to track the MCSs and their anvils as long as possible.

One way to improve the identification of CEs is by the application of the “Detect and Spread” (DAS) method (Boer and Ramanathan 1997). The DAS method basically uses multiple threshold TBBs to delineate a CE, assuming that the cloud has an optically thick core with an optically thin edge. Using a TBB of 285 K as the warmest definition of clouds over the western Pacific, the first step of their method is to detect a potential CE associated with deep convection (corresponding to a TBB of 240 K). The potential CE is spread to its edge until the limit of the spreading level is reached. The spreading limit is set to exceed the TBB detection level by 15 K. This spreading step is the process of obtaining the optically thinner part of the deep convection. The TBB for detection is then increased by 10 K at each following detection step to obtain other CEs. The detection and spreading
processes repeat until the last detection step. Unfortunately, the original DAS method only performed well in the case of isolated clouds; thus, it was not optimal for separating convective systems with shared anvils. Fiolleau and Roca (2013) developed a three-dimensional version of the DAS algorithm by involving time dimension in the detection and spreading processes. Their aim was to segment MCSs defined by 235 K, and the algorithm was able to perform well in separating two convective cores with connected anvils. Compared to the original DAS method, Fiolleau and Roca (2013) used a smaller TBB step of 5 K for convective core detection and spreading.

In this study, we incorporated the principles of the DAS method into the GTG algorithm (hereafter GTG-DAS), specifically in the CE detection process, to separate a large CE into several smaller CEs. We used different coldest and warmest thresholds and a different step for CE detection from those described by Boer and Ramanathan (1997). In our application, the detection started from a coldest threshold TBB at 210 K to delineate the core of CEs, progressing to the warmest threshold at 240 K with a 5 K step, similar to the step used by Fiolleau and Roca (2013). While there was a possibility for exploring the threshold TBB and the step for detection and spreading, the configuration of CE delineation used in this study employed the combination from previous studies that gave the most reasonable result based on several trial-and-error experiments. In case there were two adjacent convective systems with a connected anvil, an additional criterion of 1 K was applied on the spreading process to determine the cloud system edge.

We checked the improvement of MCS identification by applying the modified GTG to the data on February 6, 2016. Figure 1 shows the MCSs segmented by the original GTG that used the simple threshold method (GTG-default) and by the improved GTG in which DAS was integrated in the algorithm (GTG-DAS). By looking at the TBB value, we can infer that more than one convective cell existed within the cloudy area between 104° and 110°E. However, GTG-default was unable to separate this cloudy area as two different CEs, owing to some connecting pixels located at around 6°S and 106°E; thus, only one MCS could be identified (Figs. 1b, e). Meanwhile, GTG-DAS was successful in separating this large connected cloud area into several CEs; hence, two MCSs were identified at 1500 UTC (Fig. 1c) and four MCSSs were found at 1800 UTC (Fig. 1f). The current GTG-DAS gave satisfactory results, but more improvement is needed for computational efficiency, considering GTG-DAS was about six times slower than the original GTG.

4. Results and discussion

4.1 MCS under the influence of the MJO

Java Island of Indonesia exhibits a seasonal rainfall peak in boreal winter. The maximum occurrence of MCSs in Java can be observed during this season (Putri et al. 2017). The first case study of MCS over Java on February 6–7, 2016 coincided with an active phase of Madden-Julian Oscillation (MJO) over the Maritime Continent (phase 4). According to the real-time multivariate (RMM) MJO index developed by Wheeler and Hendon (2004), the MJO intensity was above 1.5 during the period of study. The active phase of MJO is well known for enhancing large-scale convective activities over the Indonesian Maritime Continent (Hidayat and Kizu 2010). Therefore, in this case, MJO created a more favorable atmospheric condition for the development of organized convective systems (i.e., the MCSs). With the newly developed GTG algorithm and AHI observations, we will discuss the evolution and characteristics of MCSs during the active phase of MJO as follows.

Figure 2 shows the evolution of MCSs over Java Island on February 6–7, 2016. The wider coverage of AHI spectral bands enables the construction of red/green/blue (RGB) images (the upper panels of sub figures in Fig. 2); thus more information is available from a single spatial image. We utilize the TBBs of bands 11-14/15-16/13 as the RGB channels to create these false color images. By using this RGB combination, convective clouds will appear bright white, cirrus-type clouds will have pink color, and low-level clouds will have a greenish-gray appearance. The lower the cloud top, the gray color shifts to dark green, and it becomes almost black for the clear-sky area. The MCSs identified by GTG-DAS are displayed below their respective RGB images.

In general, a wide coverage of both thick clouds and underlying lower level clouds was visible within the two-day period. Several individual convection were initiated inland at around 0700 UTC (local time is UTC+7) on February 6 (Fig. 2b). These individual cells became taller, as suggested by brighter white appearance, and became larger at the consecutive times; the thick part of their anvils merged to form a larger system at around 1200 UTC (Fig. 2d). From the perspective of MCS segmentation, GTG-DAS successfully identified two different MCSs over Java Island at 0900 and 1800 UTC (Figs. 2c, f). The convections starting at 0700 UTC in the middle to the north of Java Island propagated northward to the Java Island at 0900 and 1800 UTC (Figs. 2c, f). The convections starting at 0700 UTC in the middle to the north of Java Island propagated northward to the Java.
Fig. 2. The evolution of MCSs around Java Island on February 6 and 7, 2016. The upper panels of the subfigures are the false color RGB images constructed from the TBB of AHI bands 11-14 / 15-16 / 13. The lower panels show the MCS segmentation by GTG-DAS, in which different MCSs are represented by different colors. Each number with red color in the lower panels denotes the ID of its underlying MCS.
Sea as the part of MCS #5 (turquoise color). GTG-DAS identified the other convective systems at 0900 and 1800 UTC, i.e., the MCSs #7 (purple color) and #9 (magenta color), as separate MCSs from MCS #5 in accordance with their eastward movement, which differed from the propagation of MCS #5.

The northward-moving MCS developed into a near circular shape at 1500 UTC with no clear tendency on the direction of anvil enlargement (Fig. 2e). The weak spreading of the anvil was caused by weak upper-level wind speed (Fig. 3a) owing to the large-scale upper-level divergence associated with MJO.
MCS #5 gained an almost complete coverage over the sea at 2100 UTC (Fig. 2g). The continuous formation of convective cells over the sea prolonged the lifetime of this MCS and created a complex situation for the MCS evolution afterwards. After 0300 UTC on February 7, MCS #5 experienced a quite complicated evolution as one part of the system merged with another CE (Fig. 2j), while the other part (MCS #22 with green color) showed a different evolution tendency and thus separated from its original MCS (Fig. 2k).

Figure 4 shows the time series of CTH and CER derived from AHI with ICAS for the MCS #5 in Fig. 2. Since ICAS can estimate COT, observation on the evolution of the deep convective part (COT > 10) and the anvil (0.1 < COT < 3.6) of the MCS can be done separately. The CER of the deep convective part is not shown due to the large uncertainty in the retrievals of clouds with COT > 5.

Figure 4a suggests that the CTH of the deep convective part generally increased from 0700 to 1000 UTC on February 6 at the beginning of MCS #5 development. The deep convective clouds grew to an altitude of 17 km, and the maximum height mode persisted until about 1500 UTC. Afterwards, the mode of CTH (red color) shifted to a lower altitude and the median of CTH decreased until 0100 UTC the next day, when a considerable increase of CTH suddenly appeared. The every 10-min observation by AHI revealed some up-and-down patterns in the CTH of the deep convective cloud displayed as yellow streaks with negative slopes in Fig. 4a. A notable, local negative slope (i.e., the yellow streak) can be found between 1000 and 1300 UTC during the period of the maximum height, and similar local slopes can be observed several times after 1500 UTC. These local negative slopes indicate the weakening of dominant

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Fig. 4. The distribution of ICAS cloud properties for the MCS #5 in Fig. 2 (turquoise color) over time. (a) CTH (unit in km) of the deep convective part; (b) CTH of the anvil; and (c) CER (unit in µm) of the anvil. The deep convective part has COT greater than 10 and the anvil part has COT between 0.1 and 3.6. Shaded color denotes the proportion relative to the total number of samples at each time frame. The solid line shows the median value, while the dashed lines show the 10th and 90th percentiles. The x-axis spans from 0700 UTC on February 6, 2016 to 0300 UTC on February 7, 2016; the times on February 7 are denoted by (+1) mark.
convection within the MCS at their respective times. The sudden increase in CTH occurred right after the local negative slope because of the development of new convective cells before the cloud from the previous episode of convection vanished completely. Despite the existence of these multiple negative slopes accompanied by the local jump of CTH, GTG-DAS can capture the multiscale aspect of the segmented MCS, as suggested by the general evolution of CTH distribution (representing convective activity) that resembled the development of an individual cumulonimbus cloud but in a longer time scale. Mapes et al. (2006) summarized that in the tropical region, the progression of a larger scale weather event is similar to that of a smaller scale event, although the resemblance is more complicated than a simple superposition of the life cycle of an individual cloud system.

The anvil part of MCS #5 was not well developed until around 0800 UTC on February 6; thus the CTH and CER distributions before 0800 UTC appeared blank (Figs. 4b, c). The CTH distribution of the anvil did not exhibit noticeable local negative slope as in that of the deep convective part. However, from 1300 to 2100 UTC, the mode of anvil CTH decreased from 16 km to 14 km altitude following the decrease of the deep convective part CTH, since the anvil was formed from the advection of particles from the convective core. During the lifetime of MCS #5, the anvil CER was concentrated in the range between 10 and 30 µm (Fig. 4c). The CER had a wide distribution at around 0800 UTC, and the range gradually narrowed until 1100 UTC. The broad range of anvil CER at the earlier time might be caused by the existence of large particles owing to the advection from the precipitating cores, as suggested by Yuan et al. (2011) for the case of a young anvil. The CER of the anvil was concentrated at a considerably small value (~12 µm) from 1000 to 1600 UTC. The increase in the median of CER from 1600 until 2000 UTC may be related to the particle growth either by sublimation, ice crystal growth, and/or aggregation, as suggested by Theisen et al. (2009) for their finding on the increasing diameter of particles within the cirrus anvil with increasing time. The shifting of CER mode to a smaller value after 2200 UTC may be attributed to the new convective cells over the sea, which injected a different kind of particles to the anvil, while the older anvil from the previous convections was dissipating, and thus disappeared from the distribution.

4.2 MCS in strong vertical wind shear environment

Most of the Indonesian regions experience dry condition during the season of June-July-August as a consequence of southeast monsoons from the dry Australian region. The Sumatra region has minimum peaks of MCS occurrence and rainfall during this season, but the monthly variation is not as visible as the other subregions of Indonesia (see Fig. 7 of Putri et al. 2017). At the end of August 2015 in particular, most of the Indonesian regions exhibited a drier condition owing to a strong El Niño event (Yamanaka 2016) with a Niño-3.4 SST anomaly of 1.87 and partly to a positive Indian Ocean Dipole (IOD; Saji et al. 1999) with a Dipole Mode Index (DMI) of 0.863. However, some MCSs appeared around the northwest of Sumatra Island on August 25–26, 2015, partly because the impacts of both El Niño Southern Oscillation (ENSO) and IOD are quite weak in the northern part of Sumatra Island (As-syakur et al. 2014). Fujita et al. (2013) also demonstrated that rather than vanishing completely, the convections are confined to the northern part of Sumatra Island during the positive IOD. The aforementioned MCSs were initiated in favor to the warm SST around the northern Sumatra combined with a supporting topography and a strong vertical wind shear (Fig. 3e). The shear magnitude in Sumatra (Fig. 3e) was two to three times larger than that around Java in the previous case (Fig. 3b).

A qualitative evaluation of the RGB images (Fig. 5) suggests that August 25–26 exhibited complex cloudy scenes where convective clouds from inland Sumatra merged with the background high-cloud layer coming from the northeast direction (Fig. 5a) and low-level clouds existed under the presence of a cirrus cloud layer. Due to a large amount of connecting pixels among the existing convective cells at 1200 UTC, GTG-DAS detected an MCS with large spatial extent at the first detection time (1200 UTC). Nevertheless, GTG-DAS successfully split the MCS into two systems at 1400 UTC (Fig. 5b): one system (MCS #2) experienced immediate dissipation, while the other system (MCS #1) was enhanced by new convections that originated from the small islands and surrounding sea at around 2°S and 100°E starting from 1500 UTC (Fig. 5c). Different from the enlargement of the MCS anvil over Java Island (Fig. 2), the anvil of MCS #1 spread to the southwest direction (Figs. 5e–h) owing to the strong northeasterly wind at the upper level (Fig. 3d). After 2100 UTC, the MCS #1 dissipated, as seen from the decreasing portion of convective cloud in bright white color that was replaced by a thinner cirrus-type cloud in whitish-pink color (upper panels of Figs. 5i–l).

Figure 6 shows the distributions of CTH and CER...
Fig. 5. Similar to Fig. 2, but for the MCSs off the coast of western Sumatra Island on August 25 and 26, 2015.
for the MCS #1 in Fig. 5. Similar streaks of negative slope (as in the Java case) were visible in the CTH of the deep convective part (Fig. 6a). The CTH of the deep convective part mostly ranged from 14 to 16 km altitude with maximum height attained from 1900 to 2200 UTC; it fell rapidly after 0600 UTC on August 26 due to the dissipation of the cloud system, as suggested by the disappearance of convective clouds in bright white color (Figs. 5k, l). The highest CTH of deep convection embedded in the MCS over Sumatra (~ 16 km) is generally lower than that reached by the MCS over Java (~ 17 km). This difference may be attributed to both regional and seasonal variations of tropopause height (Reid and Gage 1981; Hashiguchi et al. 2006). Reid and Gage (1981) documented that the altitudes of tropical tropopause layer in February and August are approximately 16.7 and 15.9 km, respectively. Note that the highest CTH discussed here may not represent the overshooting tops of the MCS, but it rather represents the majority of the deep convective cloud tops.

Unlike the anvil in the Java case, the CTH of the anvil in this case was concentrated at 12–14 km altitude, and it did not experience a notable variation throughout the MCS lifetime (Fig. 6b). A moderate vertical motion existed at the upper atmosphere of the Sumatra region within the time period of analysis (Fig. 3f). Possibly, this upward motion helped maintain the particles at the upper level while they were advected by strong horizontal wind; thus, significant change was not found in the anvil CTH of the Sumatra case. Such upper level updraft was not present consistently for the MCS #5 over Java (Fig. 3c). An increasing pattern of CER in the Sumatra case was observed after the period of maximum deep convective CTH, similar to that in the first case from 1600 to 2000 UTC on February 6, 2016. However, the distribution of anvil CER of MCS #1 was concentrated between 15 and 35 µm (Fig. 6c), being slightly larger than that of the Java case. Note that the ICAS CER derived from infrared radiances is likely to represent the uppermost part of the cloud (Iwabuchi et al. 2018). Thus, it is possible that the smaller value of CER in the Java case is caused by fewer amounts of large particles at the
upper part of the anvil. In the Sumatra case, possibly strong upper level wind enabled the large particles from convective core to spread widely before they fall to the lower altitude, and the existence of persistent upper level updraft (Fig. 3f) supported these large particles to stay in the upper part of anvil cloud.

5. Summary

In the present study, we have shown the possibility of MCS tracking by using the GTG algorithm applied to the infrared data of AHI onboard the Himawari-8 satellite. Some adjustments were necessary to obtain the MCS segmentation in more detail when using the high spatial resolution of AHI data. Therefore, we incorporated the DAS method into the GTG algorithm (GTG-DAS) to get an improved delineation of the CEs that compose the MCSs. Our configuration for the GTG-DAS method yielded satisfactory results of MCS identification in our case studies, despite the limitation in the determination of the threshold TBB and TBB step.

We utilized the AHI data to study the evolution of MCSs over two Indonesian sub-regions, specifically over Java Island on February 6–7, 2016 (first case) and the off coast of western Sumatra on August 25–26, 2015 (second case). The evolutions of these MCSs were successfully tracked by using the improved GTG-DAS method. The physical properties of clouds within the MCSs were retrieved by applying the ICAS algorithm to AHI infrared bands, and were observed continuously in both daytime and nighttime. The temporal variation of CTH of the deep convective area was similar between the two MCS cases: the CTH increased at the beginning of the MCS lifetime and decreased as the MCSs progressed to dissipation. Nevertheless, the average CTH in the first case was larger than that in the second case, possibly owing to the difference of the tropopause height in the two cases. The median CTH of the anvil in the first case showed a large variation ranging from 14 to 16 km, while the second case showed a relatively stable CTH at around 13 km. The anvil CER was larger in the second case than in the first case, although the temporal variations were relatively similar to each other. The persistent, strong upper-level wind in the second case was likely the explanation for the small variation in the anvil CTH and one supporting factor for larger value of CER compared to the CER in the first case.

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