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Cover Page Footnote
The authors wish to thank Dr. John D. Tuttle of the National Center for Atmospheric Research for the valuable discussion on the cloud tracking algorithm. Infrared brightness temperatures were provided by Kyoto University, while X-band radar data were provided by Shimane University. Therefore, Dr. H. Hashiguchi (Kyoto University) and Dr. Toyoshi Shimomai (Shimane University) are acknowledged for their support in providing the necessary data. Daily mean OLR and the NCPEP-NCAR reanalysis were provided by the NOAA. The X-band radar observation and other Equatorial Atmospheric Radar (EAR) facility at Koto Tabang are supported by Grant-Aid for Scientific Research on Priority Areas, which is funded by the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) of Japan. This study was partially supported by the Faculty of Mathematics and Natural Science, Andalas University, under Hibah Mandiri-2014.

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Statistical Properties of Cloud Propagation over Sumatra during CPEA-I

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Abstract

Cloud propagation over Sumatra and the surrounding area (10◦S-10◦N, 70◦-120◦E) during the Coupling Processes in the Equatorial Atmosphere-I (CPEA-I) campaign (10 April to 9 May 2004) was tracked using brightness temperature (\(T_{\text{b}}\)) data from the GOES-9 satellite. The cloud tracking was based on three-dimensional data with a threshold of \(T_{\text{b}} < 210\) K. During the campaign, westward-moving clouds were more dominant than eastward-moving systems, with a ratio of approximately 4:1. This characteristic coincided with the dominant easterly wind aloft. Most clouds propagated with a speed varying between 4 and 35 m/s, with a mean value of 13.7 m/s. If the westward and eastward propagations were separated, the average duration, speed, and span of the westward (eastward) moving clouds are 7.7 (5.8 h), -14.5 (9.8 m/s), and 435.5 (187.1 km), respectively. The characteristics of cloud propagation during the CPEA-I were influenced by environmental factors such as relative humidity, temperature, the vertical movement of air, and wind shear. Such factors interacted with the inactive and active phases of the Madden-Julian Oscillation.


Keywords: brightness temperature, cloud propagation, Madden-Julian Oscillation, Sumatra

Introduction

The study of cloud propagation is important because it determines the distribution of precipitation in a given location [1-3]. The variability of precipitation is strongly related to cloud propagation. In tropical regions such as Indonesia, precipitation varies significantly in terms of area and time due to the location and geographical complexity as well as global atmospheric circulations such as monsoon, El Niño-Southern oscillation (ENSO), and the Madden-Julian oscillation (MJO) [4-5]. Such variability limits the accuracy of quantitative precipitation forecasts (QPF) based on numerical weather prediction (NWP) models. A more thorough understanding of convective clouds includes factors associated with propagation, dissipation, and regeneration, which may provide substantial improvements in forecasting accuracy [1].

Sumatra plays an important role in cloud propagation over Indonesia [4], even in terms of the global precipitation cycle [6]. The highly elevated terrain over Sumatra and the island’s position, as well as the direction of Sumatra, influence cloud propagation and wind patterns over Indonesian [4]. The wind field in the western part of Sumatra is different from that in the eastern part [7]. Mori et al. [4] observed the diurnal cycle of precipitation around Sumatra. They identified...
the peak of rainfall during the day moving from the western coastline of Sumatra toward the interior of the country (i.e., inland), and rain moving to the coastal areas during the night. This finding was reinforced by the results of Sakurai et al. [8], who used data from the Geostationary Meteorological Satellite (GMS-5).

Cloud propagation studies over Sumatra have so far been conducted using the diurnal frequency of the Hovmöller diagram [4,8]. Recently, Marzuki et al. [9] provided a comprehensive follow-up of previous studies by analyzing the propagation of individual clouds. However, their cloud tracking algorithm was also based on the Hovmöller plot (i.e., two-dimensional (2D) data). The Hovmöller plot is produced by averaging the data into zonal or meridional directions so that cloud tracking based on such a plot provides the cloud propagation properties (e.g., speed, lifetime, span) for only one direction: zonal or meridional. Therefore, to overcome such a limitation, cloud tracking over Sumatra using three-dimensional data (time-longitude-latitude coordinates) has been performed. The Tracking Radar Echoes by Correlation (TREC) method [10] was used to calculate the statistics of the speed, direction, lifetime, span, size, formation, genesis, and dissipation of clouds during the Coupling Processes in the Equatorial Atmosphere (CPEA) campaign-I (9 April to 10 May 2004). A detailed description of the campaign can be found in Fukao et al. [11]. The possible environmental effects on cloud propagation were discussed by analyzing wind, temperature, and humidity data.

Methods

The region of interest of this study is Sumatra and the surrounding areas (10° S-10° N and 70°-120° E). Hourly brightness temperatures (Tb) retrieved from the infrared channel 1 (IR1) of the Geostationary Operational Environmental Satellite-9 (GOES-9) are used to determine the cloud propagation properties during the CPEA-I (9 April to 10 May 2004). The spatial resolution of the data is 0.05° for both latitude and longitude. A weather radar of a 9 GHz frequency that is installed at Koto Tabang, West Sumatra, is also used, particularly in order to determine the threshold of Tb that can be assumed as a proxy for the rainfall. The radar and Tb plots for the same time and coverage of observation area will be compared with each other and the closest value to the radar image will be used as the Tb threshold. Several Tb values that have been used in previous studies (i.e., 210 K [12], 220 K, 230 K [8,9,13-15], and 240 K) are examined. Another source of data used in the present study is the National Centers for Atmospheric Prediction and the National Center for Atmospheric Research (NCPEP/NCAR) reanalysis [16]. The daily outgoing longwave radiation (OLR), wind, omega, temperature, and humidity of the reanalysis are used to observe the environmental conditions during the campaign.

As mentioned in the introduction, the TREC method is used to obtain the statistics concerning cloud propagation. A detailed explanation of this method can be found in [10]. In general, the tracking steps are as follows. First, the contour levels that would be considered to be a cloud based on the threshold value, the minimum area (grid number) to be considered as a cloud, and the amount of time that will be processed are all defined. Second, each cloud detected at a given time point will be correlated with the data from the next time point to determine the cloud’s motion vectors. In this step, the centroids of all possible clouds at a given time point are obtained. Data for as far as six degrees from the centroid are correlated with the data at the next time point. Correlation is investigated at different positions in order to obtain the position with the maximum correlation. The position of the maximum correlation determines the displacement vector of the cloud (i.e., the displacement of the cloud at a given time point to the next time point). By determining the initial and the final position of a cloud, as well as its lifetime, the speed and span can be calculated. Finally, the tracking results are checked by observing the propagation of a given cloud on the contour plot.

Results and Discussion

General cloud and wind conditions during CPEA-I.

Figure 1 shows the data concerning the OLR and wind during the CPEA-I. The data are averaged over two periods, namely 10-18 April and 19 April-9 May 2004. The two periods represent the inactive and active convective phases of Madden-Julian oscillation, respectively [17]. A detailed review of MJO can be found in [18]. Two levels of wind (i.e., 850 and 300 mb) are plotted in Figure 1, representing the lower and upper troposphere, respectively. During 10-18 April, cold cloud tops that are indicated by low OLR values (red contour plot) are only observed around Sumatra and Kalimantan. Moreover, the number of clouds over the open ocean is small. This indicates that convection over land is dominant during the inactive phase of MJO. On the other hand, cold cloud tops are observed not only over Sumatra and Kalimantan but also over the Indian Ocean during the active MJO phase. This indicates that in addition to land-based convection, the convection over the ocean is also significant during the active phase.

A significant difference in the upper troposphere wind for the two periods is not observed. Easterly winds are dominant for both periods. In the lower troposphere, the wind direction is not uniform, with easterly and westerly winds frequently observed. However, in western equatorial Indonesia, the westerly wind is dominant (Figures 1a and c). During the active phase, the westerly wind is more dominant in the lower troposphere than during the inactive phase, which is consistent with the MJO phase characteristics described by previous studies [18].
One of the most interesting features of the CPEA-I are the super cloud clusters (SCC) that cross Sumatra during three time periods, namely 23-24 April, 28-29 April, and 5-6 May (Figure 2). These SCCs are labelled as SCC1, SCC2, and SCC3 (Figure 2). The speed of SCC propagation is about 10-15 m/s to the east [17]. The propagation of SCC1 and SCC2 is blocked by the island of Sumatra [7,11], while SCC3 crosses Sumatra in a way associated with the westerly west burst (WWB) [17].

**Threshold of brightness temperature (T_b).** Figure 3 shows a comparison between the radar and satellite images for some selected T_b thresholds. To avoid the ground clutter from the mountainous area, the radar data

Figure 1. Average OLR and wind for 10 to 18 April 2004 at 850 mb (A) and 300 mb (B), and for 19 April to 9 May 2004 at 850 mb (C) and 300 mb (D)

Figure 2. Hovmöller Plot of T_b <210 K during the CPEA-I with an Averaging Window of 4° (2°N-2°S). The Arrows Indicate the Movement of Each SCC. The Symbols S and K Indicate Sumatra and Kalimantan, Respectively
are only plotted in the area 15 x 15 km to the north-south and 40 x 40 km to the west-east of the radar. The radar data are averaged hourly following the resolution of $T_b$. The similarity between the two images can be seen for $T_b < 230$ K, $T_b < 220$ K, and $T_b < 210$ K. Such values have been used by authors such as Arkin [13, 14] for $T_b < 235$ K and Fu et al. [15] for $T_b < 215$ K to observe high convective clouds in the tropics. Sakurai et al. [8] and Marzuki et al. [9] used $T_b < 230$ K to observe the cloud propagation over Indonesia from 2D data. To choose one of the aforementioned thresholds, a linear regression between the radar and $T_b$ data is employed. Theoretically, the higher the value of $T_b$, the less likely it is to rain (negative correlation), and from the regression, only $T_b < 210$ K has such a characteristic. Therefore, the value of $T_b < 210$ K is used in this study. This value is the same as that used by Zuidema [12] to observe convective clouds over the Bay of Bengal.

Cloud characteristics during CPEA-I. Figure 4 shows the time series of an individual cloud cluster during the CPEA-I based on the tracking techniques used in this study. Large clouds with an area of $14.5 \times 10^5$ km$^2$, $15.5 \times 10^5$ km$^2$, and $21 \times 10^5$ km$^2$ are observed on 23, 24, and 27 April 2004, respectively. During this period, three SCCs formed in the Indian Ocean and moved eastward, before finally disappear over Indonesia (Figure 2). In the present study, our focus is not on SCC propagation but rather on the individual clouds that are constituents of the SCC. The SCC is like an envelope consisting of many smaller clouds, which are known as a cloud cluster (CC). Thus, Figure 4 shows the properties of the CC.

Figure 5 shows a scatter plot of span versus cloud duration during the CPEA-I. Most clouds move with a speed in the range of 4-35 m/s, with an average speed of 13.7 m/s. This value is slightly different from that obtained using 2D data, which indicated that most clouds move with a speed in the range of 6-30 m/s [1-3, 9].

The speed of a cloud may vary depending on the direction. One of the advantages of cloud tracking using 3D data is the possibility to determine cloud propagation properties in all directions. Figure 6 shows the distribution of cloud direction during the CPEA-I, with the north direction indicated by $0^\circ$, east indicated by $90^\circ$, south indicated by $180^\circ$, and west indicated by $270^\circ$. It is clear that the most clouds are observed in the southwest (225$^\circ$) to northwest (315$^\circ$) directions. This is consistent with the characteristics of the upper troposphere wind (Figure 1). The relationship between wind and cloud direction has previously been reported by several researchers [6, 10, 20]. To examine the direction dependent on cloud speed, the direction is classified into four categories: $0^\circ$-$90^\circ$, $90^\circ$-$180^\circ$, $180^\circ$-$270^\circ$, and $270^\circ$-$360^\circ$ [12]. The clouds propagating toward $180^\circ$-$270^\circ$.  

![Figure 3. Comparison between the Radar Data with Some $T_b$ Values. The Radar Data are the Radar Reflectivity Factor in the Logarithmic Scale (dBZ), which Relates to the Intensity of Rainfall](image-url)
(Figure 7c) and 270°-360° (Figure 7d) are faster than those propagating in the other directions, with an average speed of 14.8 and 14.3 m/s, respectively. Clouds in the direction of 0°-90° and 90°-180° move with an average speed of 9.5 m/s and 8.4 m/s, respectively.

As discussed above, earlier studies on cloud propagation are based on 2D data so that the propagation direction is only westward or eastward. Therefore, to compare the present results with those of the existing literature, the cloud data are partitioned into two directions only: eastward (0°-180°) and westward (180°-360°). The propagation statistics for such a classification are summarized in Table 1. In general, the number of westward moving clouds is larger than the number of eastward moving clouds, with a ratio of about 4:1. This ratio is larger than that obtained by Marzuki et al. [9], whose ratio of 3:1 varied from season to season. Westward moving clouds have a duration, speed, and span larger than those of eastward moving clouds, which is consistent with the findings of previous studies [1-3, 8-9]. However, the statistical values of cloud propagation in this study differ from those of previous studies.

Mori et al. [4] obtained determined the speed of eastward and westward moving clouds over Sumatra to be 7.4 m/s and -11.1 m/s, respectively, with a span of 400 km. Furthermore, Love et al. [19] found the span of westward moving cloud systems to be 800 km. Recently, Marzuki et al. [9] found the average duration, speed,
Figure 6. Direction of Cloud Propagation during the CPEA-I. Results are Shown for 12 Bins (30 Degrees Each), as Measured Clockwise from North (0°).

Figure 7. Scatter Plot of Span versus Duration for the Direction of (A) 0°-90°, (B) 90°-180°, (C) 180°-270°, and (D) 270°-360°. The Straight Line Shows the Average Speed of Cloud Propagation.

Table 1. Statistics of Cloud Propagation during CPEA-I. Positive and Negative Speed Values Indicate Eastward and Westward Propagation, Respectively

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Mean</th>
<th>Median</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Westward (494 cloud):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Duration (h)</td>
<td>7.7</td>
<td>6.0</td>
<td>5.6</td>
</tr>
<tr>
<td>Speed (m/s)</td>
<td>-14.5</td>
<td>-11.6</td>
<td>10.0</td>
</tr>
<tr>
<td>Span (km)</td>
<td>435.5</td>
<td>287.1</td>
<td>465.3</td>
</tr>
<tr>
<td>Eastward (117 cloud):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Duration (h)</td>
<td>5.8</td>
<td>4.0</td>
<td>4.1</td>
</tr>
<tr>
<td>Speed (m/s)</td>
<td>8.9</td>
<td>6.2</td>
<td>7.6</td>
</tr>
<tr>
<td>Span (km)</td>
<td>187.1</td>
<td>121.0</td>
<td>184.7</td>
</tr>
</tbody>
</table>
and span of eastward moving clouds over Sumatra to be 18-20 hours, 12-19 m/s, and 700-1200 km, respectively. The most significant difference between the results of the present study and those of previous studies is the value of the span. The span obtained in this study is much shorter than that found in previous studies. Unlike cloud tracking based on 2D data, tracking based on 3D data does not involve any averaging procedure. Thus, the span obtained in this study is likely to be closer to the real value of cloud propagation.

Large clouds are typically characterized by a farther distance (Figure 5) and a longer duration (Figure 8). To give an idea of the location of the genesis, maximum size, and dissipation of clouds, the data are classified into three groups based on their maximum radius ($r_{\text{max}}$): $85 < r_{\text{max}} < 140$ km, $140 < r_{\text{max}} < 210$ km, and $r_{\text{max}} > 210$ km, as suggested by Zuidema et al. [12]. Clouds with a maximum radius of less than 85 km are generally sustained for less than 2 hours [22]. Figure 9 shows the location of the genesis, maximum size, and end of large clouds. In general, such a cloud formation occurs over the Indian Ocean, although it is also observed over the land. The most cloud genuses occur at 06.00-9.00 UTC and reach maximum size with a peak at 12.00 UTC. Some clouds reach maximum size at 21.00-24.00 UTC. The clouds that reach maximum size at 12.00 UTC occur over the land and the sea near the coast, while the clouds that reach maximum size at 21.00-24.00 UTC occur over the open ocean [1]. During the CPEA-I, 96 large-sized clouds are observed, with an average speed, duration, and span of 18.16 m/s, 13.72 hours, and 832.1 km, respectively.

Figure 10 shows the location and time of the clouds with a maximum radius of 140-210 km. The most clouds are initially formed at 06.00-09.00 UTC over the Indian Ocean and the land. The peak of the maximum size is observed at 09.00 UTC over the Indian Ocean and the land. The peak of cloud dissipation is observed at 12.00 UTC. About 132 clouds are classified as medium-sized clouds, with an average of speed, duration, and span of 16.8 m/s, 8.4 hours, and 524.4 km, respectively. These cloud propagation properties are larger than those of smaller-sized clouds (Figure 11). Small-sized clouds are dominant over the mainland of Sumatra and Kalimantan, and the most geneses are observed at 09.00 UTC. Small clouds over the mainland

![Figure 8. Scatter Plot of Duration (h) versus Maximum Radius of the Cloud (km)](image)

| Table 2. Statistics of Cloud Propagation during CPEA-I for the Active MJO Phase |
|---------------------------------|-------|------|--------|
| Parameters                     | Mean  | Median | Standard deviation |
| Westward (343 cloud):          |       |       |                    |
| Duration (h)                   | 7.6   | 6.0   | 5.5               |
| Speed (m/s)                    | -15.1 | -12.2 | 10.1              |
| Span (km)                      | 439.6 | 307.5 | 444.7             |
| Eastward (69 cloud):           |       |       |                    |
| Duration (h)                   | 5.7   | 4.0   | 4.4               |
| Speed (m/s)                    | 9.7   | 6.2   | 8.0               |
| Span (km)                      | 202.9 | 121.0 | 206.2             |
Table 3. Same as Table 2, but for the Inactive MJO Phase

<table>
<thead>
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<th>Parameters</th>
<th>Mean</th>
<th>Median</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Westward (151 cloud)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Duration (h)</td>
<td>7.9</td>
<td>6.0</td>
<td>5.7</td>
</tr>
<tr>
<td>Speed (m/s)</td>
<td>-13.2</td>
<td>-9.5</td>
<td>9.8</td>
</tr>
<tr>
<td>Span (km)</td>
<td>426.1</td>
<td>236.2</td>
<td>510.5</td>
</tr>
<tr>
<td>Eastward (48 cloud):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Duration (h)</td>
<td>6.0</td>
<td>4.5</td>
<td>3.7</td>
</tr>
<tr>
<td>Speed (m/s)</td>
<td>7.9</td>
<td>6.3</td>
<td>7.1</td>
</tr>
<tr>
<td>Span (km)</td>
<td>164.4</td>
<td>120.7</td>
<td>147.6</td>
</tr>
</tbody>
</table>

are the result of land-based convection and local circulation such as the land-sea breeze [23], particularly during the inactive MJO phase. During the CPEA-I, 259 small clouds are observed, with an average speed, duration, and span of 12.2 m/s, 6 hours, and 273.2 km, respectively.

Although the majority of peaks of cloud genesis, maximum size, and dissipation are observed at a certain time (Figures 9-11), such peaks are also observed at other times. This indicates the complexity of cloud formation and propagation over the Indonesian Maritime Continent. We have previously discussed the environmental conditions during the CPEA-I, as well as the relationship observed between the direction of cloud and wind. The majority of clouds move westward, which coincides with the dominant easterly winds during the CPEA-I (Figure 1). The MJO may also influence cloud propagation [3,9,20-21]. Tables 2 and 3 summarize the cloud statistics during the CPEA-I for the inactive and active phase of the MJO, respectively. The ratio of westward to eastward moving clouds for
the two MJO phases is different in that it is approximately 5:1 for the active phase and 3:1 for the inactive phase. Therefore, the number of clouds is larger during the active phase, which is supported by the environmental conditions. Figure 12 shows the value of humidity, temperature, vertical air motion (omega), and wind shear during the CPEA-I for the two phases of the MJO. Upward motion, which is characterized by a negative omega, is more clearly observed in the active phase of the MJO. Upward moving air, high humidity, and low atmospheric temperatures in the upper atmosphere indicate the potential for the formation of clouds. This is consistent with the large number of clouds observed during the active MJO phase. Relative humidity and temperature strongly influence convective clouds [22-23]. Further, humid and cooler environments favor long-lived cloud systems, as observed during the active phase of the MJO.

Figure 10. Same as Figure 9, but for the Clouds with a Maximum Radius of between 140 and 210 km

Figure 11. Same as Figure 9, but for the Clouds with a Radius between 85 and 140 km
Figure 12. The Average Relative Humidity during (A) 10 to 18 April and (B) 19 April to 9 May; the Average Temperature during (C) 10 to 18 April and (D) 19 April to 9 May; and the Average Vertical Air Movement during (E) 10 to 18 April and (F) 19 April to 9 May. The Data for (A) to (F) were Averaged from a Level of 700 mb - 400 mb, while the Wind Shear (G-H) was Averaged from 925 mb - 600 mb.

Conclusions

The present study shows that statistics concerning cloud propagation over Sumatra vary depending on the direction, cloud size, and MJO phase. In general, the number of westward-moving clouds is higher than the number of eastward-moving systems, with a ratio of approximately 4:1. The ratio varies depending on the
MJO phase, being approximately 5:1 during the active phase and 3:1 during the inactive phase. This characteristic coincides with the dominant easterly wind aloft. Most clouds propagated with an average speed of 13.7 m/s, varying from 4 to 35 m/s. The average duration, speed, and span for westward-moving clouds are 7.7 h, -14.5 m/s, and 435.5 km, respectively, while for the eastward moving clouds they are 5.8 h, 9.8 m/s, and 187.1 km, correspondingly. The number of clouds is higher during the active phase, which is supported by the environmental conditions. During the active MJO phase, upward moving air, high humidity, and low atmospheric temperatures in the upper atmosphere all indicate the potential for the formation of clouds. Additionally, humid and cooler environmental factors also favor long-lived cloud systems. This study can serve as an additional reference in the ongoing effort to improve the accuracy of quantitative precipitation forecasts based on numerical weather prediction models for tropical precipitation. To strengthen the current results, more datasets are being analyzed, and the results will be published in a subsequent paper.

Acknowledgments

The authors wish to thank Dr. John D. Tuttle of the National Center for Atmospheric Research for the valuable discussion on the cloud tracking algorithm. Infrared brightness temperatures were provided by Kyoto University, while X-band radar data were provided by Shimane University. Therefore, Dr. H. Hashiguchi (Kyoto University) and Dr. Toyoshi Shimomai (Shimane University) are acknowledged for their support in providing the necessary data. Daily mean OLR and the NCPEP-NCAR reanalysis were provided by the NOAA. The X-band radar observation and other Equatorial Atmospheric Radar (EAR) facility at Koto Tabang are supported by Grant-Aid for Scientific Research on Priority Areas, which is funded by the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) of Japan. This study was partially supported by the Faculty of Mathematics and Natural Science, Andalas University, under Hibah Mandiri-2014.

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