The Contribution of the Mesoscale Convective Complexes (MCCs) to total rainfall over Indonesian Maritime Continent

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Abstract. The MCCs contribution is expressed as the ratio of MCCs precipitation to the total rainfall at each grid point where MCCs identified by using infrared satellite imagery. The rainfall obtained from the Real-Time Tropical Rainfall Measuring Mission's (TRMM) data. This study found that MCCs contribute to total rainfall during 15-years over Indonesian Maritime Continent up to 20% where the greatest contribution concentrated over Central Kalimantan, South China Sea, Indian Ocean and Papua Island. The contribution of the MCCs is slightly increased in seasonally and monthly up to 24% and 30%, respectively. The greatest contribution is more existence over continent than the ocean in each season and month, except in July. The greatest contribution of the oceanic MCC concentrated in the Indian Ocean almost in each season and month. The contribution of the MCCs over Java Island is almost small in each season and month, but the contribution a slight increase during JJA. The MCC not only contribute to rainfall in the MCC area but the MCC give a contribution to its surrounding area. The frequency distribution of MCCs contribution to the total rainfall is very similar and consistent with the geographic distribution of the MCCs over the IMC during 15-years.

1. Introduction
Mesoscale convective systems (hereafter MCSs) are the largest of the convective storms that form when clouds occurring in response to convective instability amalgamate and organize upscale into a single cloud system with a very large upper cirriform cloud structure and rainfall covering large contiguous rain areas. They account for a large proportion of precipitation in both the tropics and warmer midlatitudes. A special case of the MCS is the mesoscale convective complex (hereafter MCCs), defined by Maddox [1], as an MCS that maintained a large, contiguous cold cloud shield for at least 6 h. The MCC criteria were chosen to isolate those systems that relatively rounded, with minor axis/major axis 0.7 at the time of maximum extent. These large, long-lasting organized systems are comprised of an ensemble of thunderstorms that together, often yield intense rain rates within contiguously sizeable precipitation areas and can greatly influence the hydroclimate of a region [2]. Some of the papers examined showed that the passage of an MCC changes the surface conditions over a large region and produce the heavy rainfall must be regarded as a cause of several of the hazards (flooding, localized flash floods, mudslides, and property and crop damage) produced by MCCs [e.g., 1, 3]. MCCs play also a major role in the rainfall regimes of the tropics [4][5]. The convection related to sea breeze
convergence is able to aggregate into MCCs later in the days, which move off land to give the greatest precipitation during the local morning time over the oceans [6].

Ashley et al. [7] and Fritsch et al. [8] showed that MCCs have contributed up to 60% of the total precipitation in a portion of the central USA. Laing [9] demonstrated that MCCs contributed an average of 22% of total rainfall during July - September 1987 across portions of the Sahel in Africa. Durkee et al. [10] determined that MCCs account for a considerable portion of total warm season precipitation in subtropical South America, with 11%-20% of the total rainfall in most warm seasons provided by MCCs in much of the study domain. Blamey and Reason [11] found that MCCs contributed up to 20% of the total summer rainfall in parts of the eastern region of southern Africa. Nesbitt et al. [12] have reported that MCSs (5-years data) produce as much as 90% of rainfall in certain land areas. For the global tropics, they produce more than 50% of the rainfall in heavily raining areas. Nesbitt et al. [12] were also documented that MCSs produce 50%-90%, are typical for heavy rain regions of the global tropics. MCSs contribute greater than 70% of the rainfall in the Tropics but make up a much smaller fraction of the cloud cover [2]. Yuan and Houze [13] showed that the active MCSs to be associated with 56% of tropical precipitation. The rainfall is strongly correlated with MCSs or MCCs, is highly spatially and temporally variable, and is heavily influenced by land-surface properties and large-scale circulations [14]. However, the contribution of MCC over Indonesian Maritime Continent (hereafter IMC) to total rainfalls is not yet well documented. Therefore, it is interesting to determine the contribution of MCCs to total rainfalls over IMC. In addition, previous studies raise important questions: what is the monthly, seasonal, and annual analyze of MCC contribution over IMC? So that, the overarching goals of this study is to determine the contribution of MCCs to rainfall over IMC for a period of 2001-2015.

2. Data and Method
To identify the MCC in this study, we use black body temperature (hereafter $T_{BB}$) from the Himawari geostationary satellites, operated by the Japan Meteorological Agency (JMA) that consists of Himawari-5/GMS-5 for data from January 2001- April 2003, Pacific GOES/GOES-9 for data from May 2003- June 2005, Himawari-6/MTSAT-1R for data from July 2005 - June 2010, Himawari-7/MTSAT-2 for data from July 2010 - June 2015, and Himawari-8 for data from July 2015 - December 2015. That satellite data has spatial and time resolutions 0.05°×0.05° and one hour, respectively. This paper adapts the method from Ismanto [15] and Trismidianto [16] that based on the maximum spatial correlation tracking technique (MASCOTTE) method by Carvalho and Jones [17] and almost similar way with Laing and Fritsch [18] to identify MCC with input the temperature, latitude, and longitude values for each cloud shield pixel that obtained from IR to a modified version of a computerized MCC program using MATLAB for measuring the satellite-observed characteristics of the MCCs [1] which stated that MCC have cloud shield with continuously $T_{BB} \leq -32^\circ C$ must have an area $\geq 100,000$ km$^2$ and the interior cold cloud $T_{BB} \leq -52^\circ C$ must have an area $\geq 50,000$ km$^2$. To distinguish MCCs from the other MCSs type, thus, the MCC will have a type of elliptical with eccentricity $\geq 0.7$ and life cycle of MCC about $\geq 6$ hours. This program computes the area, eccentricity, and the centroid positions of the -32°C and -52°C cold cloud shield associated with deep convection. The areal extent and eccentricity values were used to determine the duration and life cycle of the MCCs, while the centroid position indicated the path of propagation of the systems.

To determine the contribution of MCC to rainfall, we following the methods like Laing et al. [9], Durkee et al. [10], and Blamey and Reason [11] but a little different because in this paper we do not determine the storm area for MCC rainfall use the convex hull method but the MCC rainfall just determined from accumulated rainfall during the MCC event from initial stage until three or six hours after post-MCC stage at each grid point that occurs from 2001 - 2015 over the IMC and the total rainfall is accumulated rainfall over the IMC during 2001 - 2015. We make accumulated rainfall until around six hours after post-MCC stage due to MCCs are not only contribute to rainfall in the MCC area but the MCC give a contribution to its surrounding area after several hours dissipated in accordance with the results already reported by Trismidianto et al. [19]. The contribution of the MCC is expressed as the ratio of the rainfall during MCCs to the total rainfall at each grid point. The rainfall data from the Real-
Time Tropical Rainfall Measuring Mission's (TRMM) Multi-Satellite Precipitation Analysis (TMPA-RT) 3B41RT v7 data set, which has hourly temporal resolution and 0.25° × 0.25° spatial resolution [20].

3. Result and Discussion

3.1. MCC contribution to total rainfall during 15-years

A total of 1028 MCCs were identified and tracked during 15-years for a period of 2001 – 2015 as shown in figure 1 (a). The MCCs developed in several concentrated areas; some of them were over the ocean and coastal areas, and others were over inland and high elevation areas. By examining the location of the interior cloud centroid for all of the MCCs, one can see that MCCs are mostly frequent occur in nine regions as shown in red dotted line in figure 1 (a), i.e., 1) Indian Ocean (hereafter IO), 2) along the western coast of Sumatra (hereafter WS), 3) South China Sea (hereafter SCS) near of northern coastal of the Borneo Island, 4) the central Kalimantan (hereafter CK) around 3°S-1°N; 111°-115°E, 5) the east Kalimantan (hereafter EK) around 1° - 4°N; 116° - 120°E, 6) Makassar Strait (hereafter MS), 7) the central Sulawesi (hereafter CS) around 4° - 2°S; 120° - 123°E, 8) Merauke (hereafter MR) in location around of 8° - 5°S and 135.5° - 140°E and 9) Cendrawasih Bay (hereafter CB) in location around of 132.5° - 136.5°E and 4° - 1°S.

Most of the MCCs in the IMC occur on the continent than the ocean where this research found 31.23% MCCs over the IMC occurred over the ocean, 26.46% occurred over the coastal and most of the MCCs occurred in the continent around 42.32%. It is similar with the characteristics of MCC globally by Laing and Fritsch [21] that found most of the MCCs is located in continents almost of 91% though they can occur over oceans. However, MCC has a large scale are more prevalent over the oceans than on land especially over IO, and MCCs originating over the oceans are longer lasting originating over land. The continental MCC are mostly concentrated in near the mountainous and high elevation areas. A mountain breeze and a valley breeze are two related, localized winds that occur one after the other on a daily cycle which also given a contribution to convective activity over the IMC due to IMC is a unique geographical region that composed of a complex system of mountainous islands. If compared to the global population of MCCs, it is similar to Ashley et al. [7] and Laing and Fritsch [22] that found the mean location for MCC genesis and initiation for the Americas are located on the lee side of major mountain ranges, such as the Andes in South America or the Rockies in the United States.

The contribution of the MCCs to total rainfall over IMC is already observed in this research. Figure 1 (b) shows that frequency distribution of MCCs contribution to the total rainfall is very similar and consistent with the geographic distribution of the MCCs over IMC during 15-years. It is indicated that the greatest contribution of the MCCs is most frequently occur in the concentrated area of the MCC occurrences. The greater contribution of the MCCs found in several concentrated areas; some of them were over the ocean and coastal areas, and others were over inland and high elevation areas. One can see that maximum contribution of the MCCs in globally which around 18-20% are mostly frequent occur in the WS, SCS, CK, CS, MR, and IO. The greatest contribution from of them is found in the CK that reaches up to 20%. The amount of MCC is happening in this area, one of which is caused by the Borneo vortex that also related with mesoscale convective rainfall as described by Koseki et al. [23].

The greater contribution of the oceanic MCCs is just found in the IO that reaches up to 14-18%. In this area, the greater contribution of MCC occurred along the WS than on the IO because most of MCC that occurred in the IO will move to the top of the Sumatra Island (hereafter SI) when MCC extinct, so there are the effect of MCC over IO to rainfall over the SI. The oceanic MCC also give the great contribution over SCS in around 13-17%. In detail, MCCs give a contribution to the total rainfall over Papua Island (hereafter PI) reaches 14 - 18% in MR and CB. The great contribution around 13-17% also occurred off the coast of West Kalimantan (hereafter WK) and on two locations over Sulawesi, i.e., in South Sulawesi (hereafter SS) and South East Sulawesi. MCC contributed is very small in along the Java Island (hereafter JI) until East Nusa Tenggara due to MCCs was rarely found in this location.
3.2. MCC contribution to seasonal rainfall

The Season in IMC is divided into four seasons, namely in December, January and February (DJF) as the wet season, March, April and May (MAM) as a transitional season from wet season to the dry season. June, July, and August (JJA) as dry season, and September, October and November (SON) is a season of transition from dry season to the wet season. In seasonally, the greatest contribution of the MCCs to the DJF total rainfall is concentrated in the coastal area near the northern part of SI, which reached 18-22% as shown in figure 2 (a). However, a considerable contribution ranges from 14-20% also found in several locations such as CK, SCS near Sarawak, SS, on the coast of CS and MR. During DJF season, the MCC also contributed significantly to the several regions over the Pacific Ocean (hereafter PO) and the IO up to 18%. Several of previous work has reported that the characteristics of rainfall over JI are heavy rainfall during DJF season, but the few systems of MCC that occur in near the JI are just contributing up to 6% - 8%, while the contribution of the MCCs over East Nusa Tenggara is less than 6%.

The regions that have great contribution in DJF seasons are increased and expanded during MAM season as shown in figure 2 (b). The greatest contribution up to 24% found in SCS near the Brunei Darussalam and CK. The great contribution that occurs on the continent also found over Southern Sumatra and Sulawesi in several locations up to 16-20%. The contributions of MCC in several coastal regions were also great around 16-20% is in the area near the coast of North Sumatra and Malaysia, in the coastal area near WK, in the Java Sea near the coastal areas of JI and in the coastal area near MR. The great contribution also scattered in several locations in the IO and the PO, MCC also influencing the rainfall along from the JI until East Nusa Tenggara to remain weak in the MAM season, its contribution is very small along the land in this area, but the large contribution is seen in some coastal areas along this area.

During JJA, the impact of MCC to JJA rainfall is slightly less over continent where the MCC contribution just found up to 10% as shown in figure 2 (c). The MCC has a strong influence only at a few locations in the IO, in coastal areas near WK and coastal areas near MR. This was shown by the contribution is quite large compared with other regions which are about 16-22%. Figure 2 (c) also shows that the greatest contribution is just given by the oceanic MCC. The continental MCC is not too influencing to the rainfall during JJA. Figure 2 (d) shows the greatest contribution of the MCC during SON that around of more than 24% is concentrated on the Arafura Sea, Banda Sea, and the Flores Sea. The great contribution of the continental MCCs to SON total rainfall are mostly located over the CK and southern Sumatra, while the contribution of the coastal MCCs almost exists along the WS, SCS near Brunei Darussalam, MS, and CB.

Figure 1. (a) Geographical distribution of MCCs in IMC during 15-years (2001-2015). Locations are for the MCC at the time of maximum extent of the interior cloud size area when the mature stage. The circles representing the interior cloud size area ($10^3 \text{ km}^2$). The legend representing the elevation with the unit in meters (m). (b) The frequency distribution of the MCCs contribution to total rainfall during 2001-2015, the legend representing the percentage of MCC contribution.
By examining the location of the interior cloud centroid for each season, in DJF, one can see MCCs are most frequent concentrated in the continent at CK, SCS near northern Kalimantan, CS and MR as shown in figure 3 (a). However, that continental MCC has an interior cloud in small size around 50,000 - 149,999 km$^2$. In contrast, the large-size of MCC most frequently found over IO near SI. Most of them have an interior cloud in size more than 300,000 km$^2$. The MCC in medium size is also concentrated in PO. In MAM as shown in figure 3 (b), the frequency of MCCs was almost similar with DJF, but MCCs over CK became more widespread throughout to Kalimantan, and several MCCs with large size is indicated. MCCs over MR also became more widespread until Arafura Sea. Several MCCs with medium size around 200,000 - 300,000 km$^2$ was found over the SI and western coastal of the SI. The concentration of the oceanic MCC with large size still found over IO. Several MCC in small-size also occurs over JI. During JJA as shown in figure 3 (c), the continental MCC are rare occur, just found in several areas, among others; CK and northern Sumatra in small frequency. The MCCs are more concentrated over the ocean with the greatest concentration are over IO. MCC is never occurred in along JI until East Nusa Tenggara during JJA. There are five concentration regions of MCC events during SON as shown in figure 3 (d), i.e., over IO, SCS near northern Kalimantan, CK, CB, and MR. The MCC with large size is still concentrated over IO, while small size is concentrated over Kalimantan, especially CK. Overall, the frequency distribution of the MCCs contribution to the total rainfall in each season during the 15-years is very similar and consistent with the geographic distribution of the MCCs over IMC in each season during 15-years.
3.3. MCC contribution to monthly rainfall

Figure 4 shows the frequency distribution of the monthly contribution and location of the MCCs. In January, the continental MCC are concentrated in CK and CS but in small size less than 100,000 km². The MCCs with large size are predominantly the oceanic MCC that most frequently found over IO. The small size of MCC is also concentrated over the coastal of MR and the coastal of northern Kalimantan over SCS. The frequency of MCCs over the CK during February, but MCCs became widespread until to WK. MCCs is also concentrated in Lampung, southern Sumatra, and several MCC is found in the coastal of north Sumatra. The frequency of the MCC over the IO and the other ocean decreased, just occur in a few events. During March, MCCs just concentrated over CK with the frequency of MCCs which greater than February. There is large size of MCC occurs in CK. The small size of MCC is also occurred in SI, Sulawesi, and PI but in small frequency. A few of MCC with large size is also found over IO. The MCC with small size increased over CK in April, most of the MCC are also located in along western of SI. Most of them have medium size around 200,000 km². The MCC with medium size also occurs in IO near the coast of northern Sumatra. Several MCCs with small size is also found over PI and JI. Most of the MCCs that occur in May has a large size and located in IO. MCC is rarely found over Sulawesi, Papua, and Java. In June, most of the MCC concentrated over the ocean with the greatest frequency in IO. Only a few found the MCC on the continent, such as in CK and north Sumatra. Similar to May, MCC does not occur over Sulawesi, Java, and Papua. The maximum contribution of the MCCs to January total rainfall is mostly concentrated on the western near the northern Sumatra up to 30%. The MCC contributed 22-28% of the rainfall to the same area during February until May, while in June the contribution in this area less than 10%. The greatest contribution was also found in the CK for each month except June, even the contribution in this area reached more than 30% during March and April. The great contribution in the SCS near Brunei Darussalam occurs in March and April. The great contribution over Sulawesi is just found in April. The great contributions also found in the PO near Maluku which occurred in January and May. Several locations in the IO have great contributions almost on every month from January to June. The great contributions mostly occur on MR. MCCs contributed is very small over the JI.

The greatest contribution found in November in several areas that even reach more than 30% in Arafura Sea, Banda Sea, and the Flores Sea, this is possible because of there is an effect from MCC that occur over MR which moving toward that three sea areas after MCCs dissipated. The great contributions also found in several regions during November which located in the IO near Sumatra, on SCS near Borneo Island, on CK, on the coast of MR and CB.

Similar condition with November is also found in October but with the percentage less than November. During July until September and December, the contribution of the MCCs has considerably weak, where the maximum contribution just found in two small locations, like in July, the maximum contribution just found in the IO and the coastal of WK up to 18%. Even the contribution of MCCs along JI until East Nusa Tenggara is less than 4%, the same condition with August, but the contribution in the coastal of WK in August has the percentage value more than July up to 28%. Slight different to September, the maximum contribution up to 28% found in the coastal east on southern Sumatra, in the Java Sea near the CK and on Eastern Java. MCC is not too influencing the monthly total rainfall in December, where one can see that on average the contribution is less than 8%. The frequency of MCC was similar with June that only found over IO in longitude 91° - 97°E. The continental MCC is rare occur during this month. The frequency of oceanic MCC with large size over IO is increased in October and November, while in August is slightly same with July. However, this frequency decreased in September and December. In August and September, the frequency of continental MCC is slightly same with July, only a few found in the large island of the MCC. In fact, almost never occur along the JI to East Nusa Tenggara. The frequency of continental MCC over CK increased in October and November. However, this frequency decreased in August, September, and December. The coastal MCC is more concentrated in coastal of MR during October until December. Overall, similar with seasonal, the MCCs with large size more than 300,000 km² are most frequently occur over IO each month with the greatest frequency in October and November. CK is one favored region for MCC occurrences each month except
June until September, but most of the MCCs in this area have a small and medium size less than 300,000 km$^2$. Along of JI to East Nusa Tenggara is the region that rarely found of MCC events. Overall, the frequency distribution of MCCs contribution to the total rainfall in each month during the 15-years is very similar and consistent with the geographic distribution of the MCCs over the IMC in each season during 15-years.

**Figure 4.** The frequency distribution of the MCCs contribution to monthly rainfall during 2001-2015. The legend represents the percentage of the MCC contribution. The circle representing to monthly distribution of the MCCs location in IMC during 15-years (2001-2015); (a) January, (b) February, (c) March, (d) April, (e) May, (f) June, (g) July, (h) August, (i) September, (j) October, (k) November, (l) December. Locations are for the MCC at the time of maximum extent of the interior cloud size area when the mature stage. The circles representing the interior cloud size area ($10^3$ km$^2$).

### 4. Conclusion

The contribution of the MCC to the total rainfall over the IMC has been determined in this study. One of the result shows that the MCC not only contribute to rainfall in the MCC area but the MCC give a contribution to its surrounding area. Most of the MCCs over IMC in this study found at mainly continental, strongly related with orographic. Overall, the contribution of the MCCs to total rainfall over IMC just up to 20% because the rainfall in the IMC is influenced by various weather systems occurring on a range of temporal and spatial scales, from individual cumulus clouds, through cloud superclusters and tropical storms, right up to planetary scale interannual variations which constitute the ENSO. These values are less than the result by Nesbitt et al. [12], but for MCS contribution, they stated that for the global tropics, MCSs produce more than 50% of the rainfall in heavily raining areas during 5-years. The greater contribution is mostly found in the areas which a lot of the large volumetric rainfall [24] and higher annual rainfall amounts [25]. Frequency distribution of the MCCs was found in this study have an almost similar pattern with the distribution of the MCSs for 4-years in IMC [26]. The greatest contribution of the MCC in this research is mostly concentrated in the continent and coastal than in the ocean. It is possibly related to the previous paper that stated most of the rainfall over IMC is concentrated...
in the land [27] and the high intensity of rainfall frequently occurs in the coastal region over the IMC [25][28].

The great contribution of the MCC over the CK and SCS near of the Kalimantan were found in each season, it is consistent with the frequency distribution of the MCC that found in each season. It is also possibly related to the cold surges and the Borneo vortex where the cold surge that also induces heavy rainfalls along the western coast of the SCS (Vietnam and Malaysia) near of the IMC, in particular when synoptic-scale cyclonic disturbances are formed near Kalimantan and the southern Philippines [29][30]. The greatest contribution of the MCC is more existence over continent than the ocean, where found almost in each season in several areas over the continent, except in July. While the greatest contribution of MCC oceanic just concentrated in IO near Sumatra in each season. The MCCs contribution over JI is almost small for each season. The result also shows that the greatest contribution of the MCC to total rainfall for DJF season are in the coastal area near the northern part of Sumatra, which reached 18-22%. The greatest contribution during MAM is relatively similar with DJF but the percentage value is a slight increase around of more than 24%. During JJA, the impact of MCC to JJA rainfall is slightly less over continent where the MCC contribution just found up to 10%. The greatest contribution of the MCC during SON that around of more than 24% is concentrated on the Arafura Sea, Banda Sea, and the Flores Sea.

In the monthly analysis, the result shows the contribution of MCCs to monthly total rainfall up to 30% in several areas. During January, the maximum contribution of MCCs to total rainfall monthly was found on the west coast near the northern Sumatra up to 30%. The greatest contribution of the continental MCCs was also found on CK for each month except June, even a percentage value in this area reached more than 30% during the month of March and April. The greatest contribution of the coastal MCCs in the SCS near Brunei Darussalam most frequently occurred in March and April. The greatest contribution of the oceanic MCC in the IO most frequently occurred in November. The great contribution of the MCCs to November rainfall is also found in some area, i.e., on the IO, SCS, CK, MR, and CB. The contribution of the MCCs along JI until East Nusa Tenggara is less than 4% in each month.

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