Climate extremes over the maritime continent and their associations with Madden-Julian Oscillation

A B Sekaranom1,2, U Suarma2 and E Nurjani2

1Research Center for Disaster (Pusat Studi Bencana) Universitas Gadjah Mada. Bulaksumur 55281 Indonesia
2Department of Environmental Geography – Faculty of Geography Universitas Gadjah Mada. Bulaksumur 55281 Indonesia

*Corresponding author: andungbayu@geo.ugm.ac.id

Abstract. Madden-Julian Oscillation (MJO) has a strong influence towards rainfall over The Maritime Continent (MC). Due to possible impacts towards extreme precipitation in this area, a study is required to determine the influence of those processes. This research aims to investigate the influence of MJO on extreme precipitations over Indonesian Maritime Continent. To investigate the influence of those three processes, satellite precipitation data from The Tropical Rainfall Measuring Mission (TRMM) 3B42 product and Real time multivariate MJO (RMM) Index are used. Several extreme indices are calculated to identify magnitude of the extremes by calculating the area coverage of a specific precipitation threshold in each climate zone. Principal component analysis (PCA) is implemented to these indices to reduce large number of data into smaller number of information. Correlation analysis is implemented to the PCA and then matched to the MJO index to identify degree of influence of each process. Comparison of winds and mean sea level pressure data during each phenomenon is conducted to identify the key elements that control the generation of extreme precipitation. The result indicates extreme rain events in Indonesia could be triggered by the MJO, particularly during phase 4-6.

1. Introduction

The Maritime Continent (MC) has an important role regarding to natural resources, agricultures, transportations, and trades in Indonesia. This area also has tropical climate variability that often generates negative effects to Indonesia [1–4]. At present, many parts of this country always inundated during the peak of rainy season due to heavy precipitations. The precipitation variability over MC varies widely on a various range of timescales from diurnal to interannual. In diurnal basis, precipitations often reach maximum in late afternoon and early evening, as affected by topography, local winds, clouds appearance, and deep convections [5–7]. In interannual basis, it is common that the area is influenced by the Asian monsoon circulation, with the peak of precipitation occurs mainly in December-February and reaches minimum around June-August [8].

The MC geographic position between the Pacific Ocean at the West part and the Indian Ocean at the East part is also causing this region influenced by processes generated by the two oceans [9–13]. Over the Pacific Ocean, different sea surface temperatures (SST) between the West and the East Pacific induce a mode of climate variability, known as the El Nino Southern Oscillation (ENSO) [14–16]. Similar process also found in the Indian Ocean, where the SST sometimes becomes higher/lower...
2. Research Methods

Precipitation data used in this study is acquired from Tropical Rainfall Measuring Mission (TRMM). Precipitation data is obtained from TRMM 3B42 product. The product contains daily precipitation data over the tropical region based on the combination of active-passive satellite rainfall data, which then calibrated with rain-gauge data. The rainfall data are obtained from Nasa Goddard Earth Sciences Data and Information Services Center (http://mirador.gsfc.nasa.gov). The data used in this study started from year 1998 to 2013. Although no validation conducted in this research, previous analysis shows that the precipitation data quality is adequate for the analysis [28–30].

In addition to the rainfall data, a Global index representing the MJO are used in this study, namely the Real-time Multivariate MJO (RMM) Index [31]. The index could represent MJO phases and amplitude. The RMM index is acquired from the Australian Bureau of Meteorology Research Centre web site (http://cawcr.gov.au/staff/mwheeler/maproom/RMM/). This index is calculated based on the Outgoing Longwave Radiations (OLR) and zonal winds data. First two principal components of empirical orthogonal functions (denoted by RMM1 and RMM2) are obtained from the data. The index (RMM1+RMM2) is used as an indication of the MJO amplitude.

Lastly, this research also use atmospheric datasets are used to explain the process of heavy rainfall development during MJO event. The datasets consist of daily wind fields at the middle troposphere (500 hPa), and mean sea level pressure data. Those data are obtained from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) (http://www.esrl.noaa.gov). Composite analysis of those data is then analyzed. From this analysis, reasons on why extreme precipitations are high under the specific MJO phases can be identified.

In the first step, heavy rain events are identified based on several indices. In general, the indices can be divided into three main groups, namely frequency indicators, intensity indicators, and extreme percent indicators as shown in Table 1 [32]. Among all the extreme indices, most of them are calculate in annual basis (each value represents one single year), for example by calculating frequency of >10 mm/year, etc. Thus, it will be lack effective to identify influences of an intra-annual phenomenon, for example during a phase of the MJO event. Another alternative is by calculating general extreme distribution (GEV) on several groups of classified data based on its phase, for example by calculating each 95th percentile distribution for MJO phase 1, phase 2, and respectively [33]. By using this technique, the differences on each phase can be easily comparable. However, it still cannot identify the level of influence of a phenomenon to the extremes.

In this paper, we conduct indices calculation based on area coverage of extreme events. The basic concept is that strong phenomena can generate extreme precipitation over large area for certain period, while weak/no phenomena generate less extremes. For example, it is already revealed that when the MJO reached phase 4-5 higher precipitations often occur at the West part of MC, in which the precipitation rates (GEV value) can be distinguishable than normal condition [33]. By using the
indices, it is also possible to measure the level of influence of each phenomenon to the extremes, for
example by measuring area with precipitation >10 mm/day, >25.4 mm/day, >100mm/day, etc. To
define area coverage over MC for analyzing the indices, we manage to classify the area based on three
climate regions. The classification namely monsoonal type (A), semi-monsoonal type (B), and local
type (C) [8]. The precipitation pattern for each climate region is similar to the previous study [28].
The area experiencing extremes are calculated for each climate region (for example by calculating area
with precipitation >10 mm/day over monsoonal climate region/Zone A).

Table 1. List of frequency indicators, intensity indicators, and extreme percent indicators as
extreme precipitation indices

| Group            | ID    | Indicator name                                      | Units |
|------------------|-------|----------------------------------------------------|-------|
| Threshold indices| R25mm | Days with 25.4mm or more rainfall                 | Days  |
|                  | R50mm | Days with 50mm or more rainfall                   | Days  |
|                  | R100mm| Days with 100mm or more rainfall                  | Days  |
| Percentile-based indices | R90p  | Very wet days (above the 90th percentile of days with rain ≥ 1 mm) | mm |
| Other indices    | R95p  | Extreme wet days (above the 95th percentile of days with rain ≥ 1 mm) | mm |
|                  | SDII  | Simple daily intensity index (average rainfall on days with rain ≥ 1 mm) | mm |

Principal component analysis (PCA) is conducted on time series of several extreme rain indices.
The PCA basically is a variable reduction process, in which we can determine underlying temporal
variance based on large number of the indices. This process is conducted by isolating a number of
components by taking account each variable as a new axis[32]. Based on redundancy of all the indices,
principal components (PCs) that account the most variance from the data can be obtained[34]. The first
PC (PC1) has the highest amount of total variance from the data, while the second PC (PC2) reflect
the second highest variance obtained from the data, which is has no correlation with the PC1. The
remaining components are also ranked based on its variance and with no correlation among each other,
similar with the PC1 and PC2. Therefore, by implementing PCA to the proposed extreme indices,
major properties of extreme precipitations in the study area can be identified. Statistical correlation
tests are then performed to identify the relationship between extreme precipitations (represented by the
PCs) with the MJO index. Pearson's Correlation are used for each pair of the data.

3. Result and discussion

Figure 1 shows the normalized frequency of heavy rain events among the three climate regions in
Indonesia. The number of heavy rain events each year are represented by 5 indices, namely R25mm,
R50mm, R100mm, R90p, and R95p. It appears that several indices show similar pattern in term of the
number of extreme events. Figure 1 shows that the blue lines, indicating monsoonal (west monsoonal)
climate, have highest variation among the other two climate zones. This figure also shows that in some
extent, there are similar pattern among each zone. For example, in 2001, a lower number of extreme
events is identified from the local climate zone (green). This low record of extreme event is also observed
from the monsoonal zone. In 2009, large number of extreme events are identified from the monsoonal
zone. This condition is also observed from the equatorial zone (yellow).
Figure 1. Changes of the extreme event frequency (normalized) using different extreme rainfall indices from 1998-2013 (annually averaged).

The principal component analysis is utilized to combine all indices in Figure 1 into smaller number of data, particularly for the 1st to 3rd principal component (PC1-PC3). Table 2 shows the explained variance for each PC. The PC1 are accounted for about 75% of heavy rain occurrence over all the zones. More than 76% of heavy rain events over the monsoonal zones could be explained by PC1, followed by local climate zone (75%) and equatorial climate zone (73%). The PC2, in general, could represent about 15% occurrence of the extreme rain events among all the climate zones. Last, the PC3 could represent about 5% of heavy rain occurrence among the entire region. In total, the PCA analysis could represent more than 96% of heavy rain events among the region. However, since PC1 have more than two-thirds of the explained variance, this research is focused in analyzing the result from PC1 data.

Table 2. Percent of explained variance from each principal component among the three climate zones

| Principal Component | Monsoonal | Equatorial | Local |
|---------------------|-----------|------------|-------|
| PC1                 | 76.78     | 73.88      | 75.95 |
| PC2                 | 15.24     | 15.48      | 15.32 |
| PC3                 | 5.65      | 6.83       | 5.96  |
| Total (%)           | 97.67     | 96.20      | 97.23 |

The comparison of PC1 from each climate zone in the study area is shown in Figure 2. The plots are based on daily PC1 data which then averaged for each year. The result shows that higher number of extreme rain events occurred at more recent years (2010s) compared to 10 years before (2000s). The increase is obvious over the monsoonal zone (blue line) compared to the equatorial and local climate zones. The increase might represent the influence of climate change over the region,
particularly in term of increasing extreme events. Therefore, the monsoonal zone might face higher problems of extreme events in the future as influenced by the climate change.

![Figure 2](image)

**Figure 2.** Plot of the annually averaged principal component (PC1) among the three climate zones.

Figure 3 shows an illustration how MJO phases could contribute to extreme rain over the study area. Cumulative extreme rainfall higher than >90th percentile (R90P) indices are plotted to identify the influence of MJO propagation. The figure shows an initial finding that the MJO possibly contributes to the extreme event occurrence, particularly at propagation phase 4 to phase 6. The extreme rain events particularly observed among the monsoonal zone located at the southern part of the study area. This result is in accordance with Figure 2, where the monsoonal zone experienced higher frequency of extreme rain events in the recent years. It appears that MJO affect the western monsoon circulation which then contribute to the extreme rainfall.

![Figure 3](image)

**Figure 3.** Cumulative extreme rainfall over >90th percentile (R90p) for each MJO phase propagation in December – February (DJF).

The MJO influence towards extreme rainfall are further investigated by correlating the PC1 with the MJO amplitude, particularly from propagation phase 4 to phase 6. The comparison is further classified into two seasons, namely the boreal winter (December-February/DJF) and the boreal summer (June-August/JJA). The result is shown in Figure 4. In phase 4 of DJF, positive correlation
between MJO and extreme rainfall mostly found in the southeast part of the study area. However, when compared to Figure 3, the correlation over North Java Sea are somehow weaker. Therefore, MJO possibly does not have strong influence in generating extreme rainfall over the area surrounding Java Island. Comparison of extreme rain occurrence in Figure 3 and DJF phase 5 also shows non-significant correlation over the south part of the study area. This condition implies that heavy rainfall over this area possibly generated by different or indirect process.

The comparison of the MJO and extreme rainfall in JJA shows different pattern compared to DJF. During phase 4, no positive correlation identified in contrast to DJF that shows positive correlation. This condition implies that the influence of MJO towards extreme rainfall depends on the season. In addition, positive correlation is found later in phase 5 and phase 6. The positive correlation mostly identified at the north part of the study area. This result reveals difference between JJA and DJF, in which the MJO influence extreme rainfall further north at JJA compared to DJF.

The reason why correlation between MJO and extreme rainfall are different between DJF and JJA is explained in Figure 5. This figure shows difference in precipitable water and vertical velocity at 500 hPa level. During DJF, higher amount of precipitable water are observed mostly at the southern hemisphere. The upward vertical velocity is also observed at the southern hemisphere. High humidity content combined with upward air movement causing heavy rain over Java, Bali, and West Timor during phase 4 of the MJO. The MJO is then slowly propagating eastward during phase 5 to phase 6. During JJA, the spatial pattern of precipitable water is shifted to the north, particularly over The South China Sea. In phase 4 of JJA, no strong correlation between MJO and heavy rainfall occurs. This condition implies that the high moisture content could trigger extreme rain events without direct influence of MJO.
In term of regional and global content, the MJO have significant influence towards consecutive period of rain events, particularly in South East Asia [3,21,31,33]. Some flood events in Malaysia and Brunei have been observed to be in coincidence with MJO wave propagation [21,33]. Precipitations tend to be stronger over South East Asian Region when MJO waves occur together with La-Nina events [3]. This is possibly due to increasing moisture due to warmer sea surface temperature over the West Pacific and propagation of warmer air temperature from East Indian Ocean due to MJO. Interaction between the MJO with regional and global phenomena therefore should be investigated deeper in the future research.

4. Conclusion
Results of this research show a linkage between extreme rain events and MJO over the study area. Although it appears that heavy rain events are observed during MJO, particularly phase 4-6, the relationship between MJO and extreme rainfall is extremely complex. It appears that the MJO influence towards extreme rainfall are indirect. It is revealed that initially, positive correlation among the two variables are occurred in the direction of MJO propagation, particularly during DJF. Heavy rainfall beyond the propagation, in general, have low correlation with MJO. In this case, the heavy rainfall appears to be generated by high moisture content that previously generated by MJO.

A better understanding on the impact of the MJO is important due to their influence to generate extreme weather. Study related to the MJO effect towards extreme precipitation in Malaysia also yields strong relationship between MJO and extreme rainfall [33]. However, the effect of those phenomena might be complex over MC since it has different climate characteristics in each region. The West part of MC is mostly affected by monsoonal climate, with peak of rainy season in December-February. The central part has double peak of seasonal precipitations due to North-South movements of the Inter Tropical Convergence Zone (ITCZ). The rest of the area, especially the East part, has local climate system that resembles inverse pattern compared to the West part [8]. Thus, further investigation related to this problem can provide important information related to climate dynamic over MC.

Acknowledgement
This research is supported by Grant of Personal Research 2019 funded by Faculty of Geography Universitas Gadjah Mada (UGM) Community Fund (Hibah Penelitian Mandiri 2019 dibiayai Damas Fakultas Geografi), with contract number 2056.45/UN1/FGE/KPT/SETD/2016.
References

[1] Ummenhofer C C, D’Arrigo R D, Anchukaitis K J, Buckley B M and Cook E R 2013 Links between Indo-Pacific climate variability and drought in the Monsoon Asia Drought Atlas Clim. Dyn. 40 1319–34

[2] Yao C, Qian W, Yang S and Lin Z 2010 Regional features of precipitation over Asia and summer extreme precipitation over Southeast Asia and their associations with atmospheric-oceanic conditions Meteorol. Atmos. Phys. 106 57–73

[3] Zhang C 2013 Madden-julian oscillation: Bridging weather and climate Bull. Am. Meteorol. Soc. 94 1849–70

[4] Marfai M A, Sekaranom A B and Ward P 2015 Community responses and adaptation strategies toward flood hazard in Jakarta, Indonesia Nat. Hazards

[5] Turk F J and Xian P 2013 An assessment of satellite-based high resolution precipitation datasets for atmospheric composition studies in the maritime continent Atmos. Res. 122 579–98

[6] Chang C-P, Wang Z, McBride J and Liu C-H 2005 Annual cycle of Southeast Asia—Maritime Continent rainfall and the asymmetric monsoon transition J. Clim. 18 287–301

[7] Sekaranom A B and Nurjani E 2019 The development of Articulated Weather Generator model and its application in simulating future climate variability IOP Conference Series: Earth and Environmental Science

[8] Aldrian E and Dwi Susanto R 2003 Identification of three dominant rainfall regions within Indonesia and their relationship to sea surface temperature Int. J. Climatol. A J. R. Meteorol. Soc. 23 1435–52

[9] Ropelewski C F and Halpert M S 1987 Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation Mon. Weather Rev. 115 1606–26

[10] Wu T-W and Qian Z-A 2003 The relation between the Tibetan winter snow and the Asian summer monsoon and rainfall: An observational investigation J. Clim. 16 2038–51

[11] Yoo S-H, Yang S and Ho C-H 2006 Variability of the Indian Ocean sea surface temperature and its impacts on Asian-Australian monsoon climate J. Geophys. Res. Atmos. 111

[12] Huang A, Zhang Y and Gao X 2007 Impacts of coastal SST variability on the East Asian summer monsoon Adv. Atmos. Sci. 24 259–70

[13] Marfai M A, Sekaranom A B and Cahyadi A 2015 Profiles of marine notches in the Baron coastal area—Indonesia Arab. J. Geosci.

[14] Choi K-S, Kang S-D, Kim H-D and Wang B 2014 The spatio-temporal characteristics of total rainfall during September in South Korea according to the variation of ENSO Clim. Dyn. 42 1139–54

[15] Grimm A M and Tedeschi R G 2009 ENSO and extreme rainfall events in South America J. Clim. 22 1589–609

[16] Sekaranom A B, Nurjani E and Pujiastuti I 2018 Cloud structure evolution of heavy rain events from the East-West Pacific Ocean: A combined global observation analysis IOP Conference Series: Earth and Environmental Science

[17] Jourdain N C, Gupta A Sen, Taschetto A S, Ummenhofer C C, Moise A F and Ashok K 2013 The Indo-Australian monsoon and its relationship to ENSO and IOD in reanalysis data and the CMIP3/CMIP5 simulations Clim. Dyn. 41 3073–102

[18] Wang X and Wang C 2014 Different impacts of various El Niño events on the Indian Ocean Dipole Clim. Dyn. 42 991–1005

[19] Izumo T, Lengaigne M, Vialard J, Luo J J, Yamagata T and Madec G 2014 Influence of Indian Ocean Dipole and Pacific recharge on following year’s El Niño: Interdecadal robustness Clim. Dyn. 42 291–310

[20] Kajikawa Y, Yasunari T and Kawamura R 2003 The Role of the Local Hadley Circulation over the Western Pacific on the Zonally Asymmetric Anomalies over the Indian Ocean J. Meteorol. Soc. Japan. Ser. II 81 259–76

[21] Tangang F T, Juneng L, Salimun E, Vinayachandran P N, Seng Y K, Reason C J C, Behera S K
and Yasunari T 2008 On the roles of the northeast cold surge, the Borneo vortex, the Madden-Julian Oscillation, and the Indian Ocean Dipole during the extreme 2006/2007 flood in southern Peninsular Malaysia Geophys. Res. Lett. 35 1–6

[22] Ramirez E M, Reid J S, Xian P, Hyer E, Turk J, Flatau M and Zhang C 2009 Relating Precipitation Phenomena with MODIS Detected Hot Spots in the Maritime Continent AGU Fall Meeting Abstracts

[23] Murtugudde R, McCreary Jr J P and Busalacchi A J 2000 Oceanic processes associated with anomalous events in the Indian Ocean with relevance to 1997--1998 J. Geophys. Res. Ocean. 105 3295–306

[24] Annamalai H, Murtugudde R, Potemra J, Xie S-P, Liu P and Wang B 2003 Coupled dynamics over the Indian Ocean: Spring initiation of the zonal mode Deep Sea Res. Part II Top. Stud. Oceanogr. 50 2305–30

[25] Yamagata T, Behera S K, Luo J-J, Masson S, Jury M R and Rao S A 2004 Coupled ocean-atmosphere variability in the tropical Indian Ocean Earth’s Clim. Ocean. Interact. Geophys. Monogr 147 189–212

[26] Fischer A S, Terray P, Guilyardi E, Gualdi S and Delecluse P 2005 Two independent triggers for the Indian Ocean dipole/zonal mode in a coupled GCM J. Clim. 18 3428–49

[27] Xie S-P, Hu K, Hafner J, Tokinaga H, Du Y, Huang G and Sampe T 2009 Indian Ocean capacitor effect on Indo--western Pacific climate during the summer following El Niño J. Clim. 22 730–47

[28] Sekaranom A B, Nurjani E, Hadi M P and Marfai M A 2018 Comparision of TRMM Precipitation Satellite Data over Central Java Region - Indonesia Quaest. Geogr.

[29] Sekaranom A B and Masunaga H 2017 Comparison of TRMM-derived rainfall products for general and extreme rains over the maritime continent J. Appl. Meteorol. Climatol.

[30] Sekaranom A B and Masunaga H 2019 Origins of heavy precipitation biases in the TRMM PR and TMI products assessed with cloudsat and reanalysis data J. Appl. Meteorol. Climatol.

[31] Wheeler M C and Hendon H H 2004 An all-season real-time multivariate MJO index: Development of an index for monitoring and prediction Mon. Weather Rev. 132 1917–32

[32] Joshi S, Kumar K, Joshi V and Pande B 2014 Rainfall variability and indices of extreme rainfall-analysis and perception study for two stations over Central Himalaya, India Nat. hazards 72 361–74

[33] Salahuddin A and Curtis S 2011 Climate extremes in Malaysia and the equatorial South China Sea Glob. Planet. Change 78 83–91

[34] Richman M B 1986 Rotation of principal components J. Climatol. 6 293–335