Cloud structure evolution of heavy rain events from the East-West Pacific Ocean: a combined global observation analysis

A B Sekaranom\textsuperscript{1,2}, E Nurjani\textsuperscript{1} and I Pudiantut\textsuperscript{1}

\textsuperscript{1}Department of Environmental Geography, Faculty of Geography, Universitas Gadjah Mada, Indonesia.
\textsuperscript{2}Institute of Space-Earth Environmental Sciences, Nagoya University, Japan.

andungbayu@geo.ugm.ac.id

Abstract. Heavy rain events are often associated with flood hazards as one of the most devastating events across the globe. It is therefore essential to identify the evolution of heavy rainfall cloud structures, primarily from global satellite observation, as a tool to provide better disaster early warning systems. To identify the mechanism of heavy rainfall systems and its relationship with cloud development, especially over The Pacific Ocean, we aim to study the westward evolution of the convective systems over this area. Several datasets from Tropical Rainfall Measuring Mission (TRMM), CloudSat GEOPROF product, and ECMWF-reanalysis (ERA) interim were utilized to characterize the evolution. Geolocation and orbital time-lag analysis of the three different datasets for more than 8 years (2006-2014) could provide information related to the evolution of cloud structures associated with heavy rain events. In the first step, a heavy rainfall database was generated from TRMM. The CloudSat coordinate and time position were then matched with TRMM coordinate and time position. All of the processes were programatically conducted in fortran programming language. The result shows a transition between East and West Pacific ocean for TMI data.

1. Introduction

Indonesia is one of the countries where a large number of flood hazards occur each year [1]. The hazards are known to be not only generated by land surface characteristics but also due to the influence of atmospheric circulation. The area surrounding Indonesia, which is also known as The Maritime Continent [2], is an area adjacent to two main warm pools over the global tropics, namely the Pacific Ocean and the Indian Ocean warm pools. Although the warm pools become the source region in terms of moisture, high precipitation amounts are found over islands surrounding the warm pools as generated by the influence of the land-sea breeze that transport moisture from the ocean to the land [3]. More interestingly, heavy rainfall over this region does not require a significant cloud top height to reach the “extreme” rain rate, but rather occur at a lower top height due to the humid environment at the lower troposphere [4].

One of the region that has a close relationship with rainfall in Indonesia is The Tropical Pacific Ocean, which has a significant role in transporting energy and moisture [5] in the East-West direction. The interaction occurs in the form of an atmospheric circulation which is known as Walker Circulation [6]. In a more specific, the circulation is called as The Southern Oscillation [7]. A significant rainfall increase over Indonesia occurs during The Southern Oscillation cold phase, where Sea Surface Temperature (SST) over East Pacific become colder than its normally observed. This condition triggers stronger westward circulation at the lower troposphere, mainly from The East Pacific to The West Pacific and reversed during the warm phase [8]. As a result, in the cold phase, increasing precipitation occurs mainly at the peak of the rainy season, particularly around December to February [9,10].

Although the atmospheric dynamics over the Pacific Ocean, including Indonesia, has been well understood, including its long-term trends [11], the differences related to the extreme precipitation
development are still unresolved. Based on previous researchers, it seems that higher SST over the Pacific warm pool produces more rain over West Pacific (including Indonesia), but less from the East to the Central Pacific. It is therefore essential to identify its dynamics, especially in terms of extreme precipitating cloud structures and environment stability from the East to the West. This paper aims to characterize the difference of extreme precipitating cloud developments from The East to The West Tropical Pacific Ocean, and further explains the differences in terms of environmental stability.

2. Research Methods
The area domains, data, and methods of this research are described in this section.

2.1. Spatial and temporal domain
The tropical area of 15°N-15°S over the Pacific Ocean was selected as a domain in this analysis, which is divided into three regions. The regions consist of Tropical East Pacific Ocean/EastPac (90°W-130°W), Central Pacific Ocean/CentralPac (130°W-180°W), and West Pacific Ocean/WestPac (90°E-180°E). The EastPac Region covers the area surrounding the West part of North and South America. The CentralPac region covers a wide area in the middle of Pacific, while the WestPac is including Western part of Pacific Ocean and The Maritime Continent. The separation of the three regions ensures the transition between the East-West circulations over The Pacific Ocean. The time domain was selected to match the availability of the three datasets from 2006 to 2014.

2.2. Data
Three datasets were used in this research, contains precipitation data from Tropical Rainfall Measuring Mission/TRMM [12], radar reflectivity from CloudSat [13], and Environmental profile from ECMWF Reanalysis (ERA) interim [14]. The population of instantaneous rain-rate from TRMM TMI 2A12 was selected as the time base of the analysis. The TMI surface flag was selected to mask out the land and coast surfaces. 94 GHz radar reflectivity data from CloudSat GEOPROF was selected to characterize precipitating clouds over the area of interest. The ERA-interim data were further used to characterize the environmental profile of heavy precipitation among the three regions. The air temperature, specific humidity, relative humidity, and vertical velocity profiles were obtained to calculate Convective Available Potential Energy (CAPE). Detailed information about the datasets used in this analysis is shown in table 1.

| Platforms    | Instruments | Description                  | Resolution                                | Target parameters                                           |
|--------------|-------------|------------------------------|-------------------------------------------|-------------------------------------------------------------|
| TRMM         | TMI         | Passive Microwave Imager     | 4.4 km (high-resolution channels) and 8.8 km (low-resolution channels) | Near-surface rain rate (TMI 2A12), TMI surface flag (TMI 2A12) |
| CloudSat     | CPR         | 94-GHz radar                 | 1.4 km × 1.7 km                           | Radar reflectivity (2B GEOPROF), CloudClass (2B-CLDCLASS)    |
| ERA-Interim  | ECMWF Reanalysis Interim | Gridded 0.75° × 0.75°      |                                           | Air temperature, specific humidity, relative humidity, and vertical velocity profiles |

2.3. Methods
The TRMM contains active and passive sensors with the primary function to estimate precipitation over earth surface. The data are available from 1998-2014 with a fine spatial resolution and 46 days revisiting time. This means that TRMM contains long-term precipitation data with extensive records.
However, due to a broad range of data recorded by TRMM, in this research the surface precipitation data from TRMM passive microwave imager (TMI) were utilized. The TMI dataset is selected in this research since passive microwave (PMW) data are widely used by many satellites, in contrast to the narrow active radar sensor. TMI data contains instantaneous rain-rate data which is estimated from 9 Passive Microwave Channels with 4.4 km² resolution. Gridded precipitation data with 0.25°×0.25° resolution was generated by using this data to produce easier match-up with the CloudSat and ERA-interim data. In this research, extreme rain events are defined as the uppermost 10% rain-rate from the TMI gridded surface rain-rate population from 2006-2014. The extreme rain database was generated using this threshold, contains information about the instantaneous rain-rate, location, and time-stamp of each data.

The CloudSat contains Cloud Profiling Radar (CPR) operated in 94 GHz and starting operated from 2006. The CPR sensor produces a finer resolution than TMI (1.7 km²), but only contain a single profile over its track. CloudSat also has a sun-synchronous orbit, measuring cloud profiles at around 2 pm local time, which is distinctly different from TMI. To match the CloudSat profiles with extreme rain identified by TMI, the corresponding CloudSat reflectivity profile are determined within the TRMM gridded 0.25°×0.25° degree resolution. The TRMM-CloudSat time differences in observing the earth surface can be beneficial to explain the cloud structure evolution from time to time [15]. A cloud fraction composite was generated to explain the development of convective clouds over time and arranged to the relative time compared to the maximum surface precipitation identified by TRMM. The highest CloudSat reflectivity within the extreme precipitating grid is selected as the coordinate center and binned within each ±1.5 hours difference. The composite cloud profiles are generated by combining data in each spatial and temporal bin. Figure 1 explains detailed illustration how composite CloudSat profile could be generated using the TRMM-CloudSat time differences. The procedure is similar to the ERA-interim data, except that the ERA-interim data records have 6 hours interval (00h, 06h, 12h, and 18h UTC) for each 0.75°×0.75° degree grid.

The composite cloud fractions were calculated to represent the cloud dimensions (width, height, and shape) accompanying extreme rain events using the CloudSat reflectivity data. In this analysis, the cloud profiles were combined in each horizontal distance bin and vertical height bin within 6 hours before and after the heavy rainfall events detected by the TMI. To represent the difference among the three regions in terms of environmental stability, Convective Available Potential Energy was calculated by utilizing the ERA-interim environmental profile. The following equation was utilized;
where $z_f$ is the height of the level of free convection and $z_n$ is the height of the equilibrium level (neutral buoyancy). $T_{vp}$ is the virtual temperature of the specific parcel, where $T_{ve}$ is the virtual temperature of the environment, and $g$ is the acceleration due to gravity.

3. Result and Discussion

The results of this research are explained in terms of the number of deep convective events, convective cloud structures, and its corresponding environmental profiles.

3.1. CloudSat deep convective events

Since heavy rainfall events are often associated with deep convective clouds, it is important to observe the occurrence of deep convective events over the global area, particularly over The Tropical Pacific Ocean. In this analysis, the CloudSat cloud-class product was combined into 0.25°×0.25° degree grid from each orbit from 2006-2014. The result of this analysis is shown in Figure 2. Based on the figure, an enormous amount of deep convective clouds has been identified across the global tropics, reaching up to 2000 observed events in total.

Although the deep convective clouds were accumulated in the tropics, the distribution of deep convective clouds itself varies among the area, especially between 15°N-15°S. From the figure, a substantial number of deep convective clouds found over Indonesia and South America. The existence of deep convective clouds over Indonesia is related to the existence of two warm pools, consisting The Pacific Ocean Warm Pool and The Indian Ocean Warm Pool. Over the Pacific Ocean, most of the deep convective clouds found at this warm pool close to Indonesia, but less from the East and Central Pacific.

![Figure 2. Number of global deep convective events obtained from CloudSat.](image)

3.2. CloudSat convective cloud structure

Several example snapshots of extreme precipitating cloud obtained from geolocated CloudSat data is shown in figure 3. The figure shows the raw reflectivity data from CloudSat profiles, which is a range from -40 dBZ to 20 dBZ. It can be observed from the figure that heavy precipitating clouds occur with considerable variation in width, from 10 to 200 km, and could reach higher than 15 km in height.
Figure 3. Example snapshot of extreme precipitating cloud from CloudSat profile data. The horizontal annotation represents distance, and the vertical annotation represents height.

To produce composite cloud fractions, highest CloudSat reflectivity and cloud-mask data corresponding to heavy precipitation grid from TMI rain events were acquired (figure 4a and 4b). The process to obtain the highest CloudSat reflectivity is intended to ensure that the convective center is positioned in the middle. Using the cloud-mask data, the cloud exterior boundaries were delineated, and each consecutive cloud cluster was labeled as a single cloud (figure 4c). Clouds that are not located at the center coordinate were masked out (figure 4d). Cloud fractions are then determined by the sum of cloud occurrence from each profile then normalized to the 0-1 range by dividing it by the maximum occurrence.

Figure 4. Cloudsat reflectivity data processing to filter out irrelevant cloud surrounding heavy rainfall and produce composite cloud fraction.

The result of composite cloud fraction is shown in figure 5. The figure represents the dimensional difference between Tropical West Pacific Ocean, Central Pacific Ocean, and East Pacific Ocean. The plot represents the development of heavy precipitating cloud from 3 hours before (top) to 3 hours after (bottom) the heavy precipitation occurs within ± 1.5 hours bin. The figure shows that heavy rainfall events over East Pacific Ocean are generated by shallower clouds with cloud top height about 7-8 km. Over Central Pacific Ocean, the cloud top heights reach up to 10 km, while over West Pacific Ocean,
the height reaches to about 12 km. From the figure, we also could observe the cloud development process from the smallest at -3 hours bin to the highest at the +3 hours bin. However, extreme precipitation events have narrower width compared to the +3 hours bin.

Figure 5. CloudSat convective cloud fractions from a) Tropical West Pacific Ocean, b) Tropical Central Pacific Ocean, and c) Tropical East Pacific Ocean from -3 hours to +3 hours relative to heaviest surface precipitation. The brighter color in the center represents significant cloud fraction above 70% of the total fraction.

3.3. Environmental Profile corresponding to heavy precipitation
The cloud structure differences between The East, Central, and West Pacific Ocean are further investigated using ERA-interim at the nearest grid position to the TRMM extreme precipitation grid. The initial comparison has been calculated from the vertical profile of air temperature, relative humidity, specific humidity, and vertical velocity data. The result shows a clear difference observed from the vertical velocity anomaly data (figure 6). The result shows that upward vertical velocity anomaly over The West Pacific Ocean reaches higher altitudes than the East and Central Pacific anomalies. This result could explain why the clouds grow larger over The West Pacific compared to the East Pacific in case of heavy rain events.

Figure 6. Vertical velocity profile anomalies from ERA-interim data corresponding to the heavy surface rain at the time center from West to East Pacific Ocean (left to right). The diagonal black line represents the difference in the height of -0.01 Pa/s anomalies.
The taller heavy precipitating clouds over the West Pacific Ocean could be explained in terms of CAPE. The result of CAPE differences among the West to East Pacific Ocean is shown in Figure 7. Based on this figure, large accumulation of the potential energy occurs 12 hours before to 6 hours before heavy precipitation events. The potential energy are then began to be consumed by the convective process from 6 hours before and after heavy precipitation events. Although the pattern is similar, The Western Pacific Ocean, in general, has a larger potential energy than the Central and East Pacific Ocean. The larger potential energy contributes to the stronger convective process in The West Pacific.

The higher CAPE generates the larger and taller extreme precipitating clouds over this region, which in turn, converted to a higher vertical velocity that contains larger moisture content to be transported to the upper part of the troposphere. The larger amount of moistures transported to the upper troposphere becomes the main factor in generating heavy precipitation over the West Pacific Ocean.

It is also worth to note that in this research, the only precipitation dataset is from the TRMM TMI. We select the TMI data since the PMW estimation is common and applicable not only for TRMM. However, in this case, the accuracy compared to the PR or ground observations are not conducted. A significant difference might exist when different precipitation datasets are included. Although comparison of PR-TMI data conducted by Sekaranom and Masunaga [4] showed that that PR-TMI differences over the ocean are less apparent than the land in The Maritime Continent, the differences might still exist and become a subject for the further research.
5. Acknowledgement
This research is funded by Lembaga Pengelola Dana Pendidikan (LPDP) Ministry of Finance Republic of Indonesia, with Contract PRJ-1875/LPDP/2014.

6. References
[1] Marfai M A Sekaranom A B and Ward P 2015 Community responses and adaptation strategies toward flood hazard in Jakarta, Indonesia Natural hazards 75 pp 1127-44
[2] Ramage C S 1968 Role of a tropical Maritime Continent in the atmospheric circulation Mon Wea Rev 96 pp 365-70
[3] Qian J H 2008 Why precipitation is mostly concentrated over islands in the Maritime Continent Journal of the Atmospheric Sciences 65 pp 1428-41
[4] Sekaranom A B and Masunaga H 2017 Comparison of TRMM-Derived Rainfall Products for General and Extreme Rains over the Maritime Continent Journal of Applied Meteorology and Climatology 56 pp 1867-81
[5] Alexander M A Blade I Newman M Lanzante J R Lau N C and Scott J D 2002 The atmospheric bridge: The influence of ENSO teleconnections on air-sea interaction over the global oceans Journal of Climate 15 pp 2205-31
[6] Julian P R and Chervin R M 1978 A study of the Southern Oscillation and Walker Circulation phenomenon Monthly Weather Review 106 pp 1433-14
[7] McBride J L Haylock M R and Nicholls N 2003 Relationships between the Maritime Continent heat source and the El Niño-Southern Oscillation phenomenon Journal of Climate 16 pp 2905-14
[8] Deser C and Wallace J M 1990 Large-scale atmospheric circulation features of warm and cold episodes in The Tropical Pacific Journal of Climate 3 pp 1254-81
[9] Ropelewski C F and Halpert M S 1989 Precipitation patterns associated with the high index phase of the Southern Oscillation Journal of climate 2 pp 268-84
[10] Chang C P Wang Z Ju J and Li T 2004 On the relationship between Western Maritime Continent monsoon rainfall and ENSO during northern winter Journal of Climate 17 pp 665-72
[11] Vecchi G A Soden B J Wittenberg A T Held I M Leetmaa A and Harrison M J 2006 Weakening of tropical Pacific atmospheric circulation due to anthropogenic forcing Nature 441 pp 73-76
[12] Simpson J Kummerow C Tao W K and Adler R F 1996 On the Tropical Rainfall Measuring Mission (TRMM) Meteorology and Atmospheric physics 60 pp 19-36
[13] Stephens G L Vane D G Boain R J Mace G G Sassen K Wang Z Illingworth A J O'Connor E J Rossow W B and Durden S L 2002 The CloudSat mission and the A-Train: A new dimension of space-based observations of clouds and precipitation Bulletin of the American Meteorological Society 83 pp 1771-90
[14] Dee D P Uppala S M Simmonds A J Berrisford P Poli P Kobayashi S Andrae U Balmaseda M A Balsamo G and Bauer P 2011 The ERA-Interim reanalysis: Configuration and performance of the data assimilation system Quarterly Journal of the royal meteorological society 137 pp 553-97
[15] Masunaga H 2012 A satellite study of the atmospheric forcing and response to moist convection over tropical and subtropical oceans Journal of the Atmospheric Sciences 69 pp 150-167