Relationship between cloud vertical structures inferred from radiosonde humidity profiles and precipitation over Indonesia

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Abstract. Knowledge of cloud vertical structure, including the presence of multiple cloud layers, is important for several climate-related applications such as for understanding the impact of clouds on Earth's radiation budget. Moreover, the vertical distribution of latent heat release that affects global circulation and precipitation. The characteristics of cloud vertical structure may change as a consequence of climate change. However, study on cloud vertical structure in Indonesia is limited to case study based on short period observation. This study aims to analyse the vertical structure of clouds, such as cloud base height (CBH), the height of the cloud top (CT) and the number of cloud layers due to climate change in Indonesia, based on ~ 30 years radiosonde observation. The relation between cloud vertical structures and precipitation was investigated. We used the radiosonde data from nine observation stations in Indonesia. On an average, it is observed that over Indonesia one-layer clouds is most frequently observed cloud, more than 60% of the time. This number is much larger than the fraction of single layer clouds over the globe which is about 58% of the time. The cloud vertical structures in Indonesia vary from month to month. The cloud vertical structure during wet and dry season is different which indicate a strong relationship between cloud vertical structure and precipitation.

1. Introduction

Clouds maintain energy balance on Earth by absorbing and reflecting solar radiation that enters the Earth's atmosphere and reduces thermal radiation [1, 2]. The radiation balance is highly dependent on the vertical structure and distribution of clouds in the atmosphere. In addition, the vertical distribution of latent heat dissipation also affects global circulation and precipitation. The impact of clouds on the radiation balance of the Earth's atmospheric system also depends on cloud top height (CT), cloud base height (CBH), and optical properties of clouds [3,4]. CBH, CT and cloud thickness are the main parameters, which greatly affect the energy exchange between the cloud layer and the ground surface [5]. This parameter can be used to determine the type of cloud based on its height.

Knowledge of cloud types is very important because the overall impact of clouds on Earth's energy budget is difficult to predict, because they involve two opposite effects depending on the cloud type [6]. Clouds with high altitude (thinner) tend to heat the surface because they trap more heat coming out (infrared) while low-altitude (thick enough) clouds tend to cool the surface because they reflect more incoming sunlight (short waves) [7].
Indonesia is a country located in a tropical area. This position resulted in the rainfall received quite high. In the tropics, the most common form of precipitation is rain. The characteristics of Cloud Vertical Structures can change as a result of climate change. Changes in cloud layer thickness with increasing rainfall. Thinner clouds are likely to have less rainfall, whereas thicker clouds are likely to have more rainfall [8].

However, research on the vertical structure of clouds in Indonesia is still very limited and mostly related to the spatial distribution of clouds from satellite imagery [9,10,11] in terms of the spatial distribution of rainfall. Therefore, a long-term observational study was carried out using radiosondes and rainfall data, with the aim of knowing the relationship between the vertical structure of clouds and rainfall in Indonesia. The radiosonde network makes it possible to take CBH, CT, and the number of cloud layers on a large scale [12], because the radiosonde can reach layers about 30 km from the earth's surface [13]. The observational data used are also longer which is ~ 30 years from nine radiosonde stations, i.e., Padang, Pangkal Pinang, Medan, Surabaya, Jakarta, Manado, Ujung Pandang, Palu, and Biak.

2. Data and Methodology

The data used in this study were radiosonde data and rainfall data for ~ 30 observations. Radiosonde data is managed by the University of Wyoming (http://weather.uwyo.edu/upperair/sounding.html), with nine observation stations in Indonesia. Rainfall data is released by GPCC (Global Precipitation Climatology Centre) (http://opendata.dwd.de/climate_environment/GPCC/html/fulldatamonthly_v2018_doi_download.html) with 0.50 spatial resolution.

Cloud parameters are determined by the method proposed by Wang and Rossow 1995 [14]: (1) Cloud base height (CBH) is determined by relative humidity RH > 84%, with four consecutive valid measurements. The RH profile for all valid soundings is checked from 600 m AGL and above, (2) The cloud top height (CT) is determined to be at least 3% jump from RH in the base line, (3) Cloud layer is determined if the humid layer has a maximum RH threshold value and minimum RH. measurements at the next height reach minimum RH again, this is called the cloud layer.

Clouds are grouped into four types based on the height of the cloud base and the thickness of the cloud layer as did Lazarus et al. 2000 [15] and Zhang et al., 2010 [16] namely (1) Low-level clouds with a small base height of 2 km and a thickness of less than 6 km, (2) medium-level clouds with a base height ranging from 2 to 5 km, (3) high-level clouds with a cloud base height greater than 5 km and (4) deep convective clouds with a small base height of 2 km and a thickness more than 6 km. then create a temporal distribution of monthly rainfall from the GPCC data.

3. Result

3.1. Vertical distribution of cloud layers and cloud types

Table 1 shows the distribution of the number of cloud layers and the percentage of cloud layer appearance from the observation station. The cloud layers observed were one-layer, two-layer, three-layer, and four-layer clouds. The most frequently observed clouds in Indonesia are one-layer clouds with the largest number of cloud observations and a larger cloud appearance percentage than other cloud layers, namely above 60% on average. This value exceeds that of cloud appearances from other countries, which is about 44%, 58% for the world region [14,17] and India country, the percentage of the one-layer cloud is about 40.80% [18]. The largest percentage of single-layer clouds in Indonesia was observed at stations of Manado (73,51%), Surabaya (72,27%), Biak (70,45%) and Jakarta (70,27%). These stations are located in areas that tend to be maritime. In areas where the ocean is dominant, the percentage of cloud appearance is quite large (tambah rujukan). Three- and four-layer clouds are rarely observed with an occurrence percentage below 6% (Table 1).
Table 1. Number of observations and percentage of cloud occurrences

| Observation Station | Number of observations | percentage of cloud occurrences (%) |
|---------------------|------------------------|-------------------------------------|
|                     | One layer | Two layer | Three layer | One layer | Two layer | Three layer |
| Padang              | 5695      | 2838      | 383        | 63.58     | 31.68     | 4.28        |
| Pangkal Pinang      | 3523      | 1334      | 195        | 69.50     | 26.32     | 3.84        |
| Medan               | 6172      | 2714      | 438        | 66.05     | 29.04     | 4.68        |
| Surabaya            | 4090      | 1374      | 168        | 72.27     | 24.28     | 2.96        |
| Jakarta             | 4803      | 1758      | 231        | 70.27     | 25.72     | 3.37        |
| Manado              | 5264      | 1676      | 195        | 73.51     | 23.04     | 2.72        |
| Ujung Pandang       | 5128      | 2195      | 321        | 67.04     | 28.68     | 4.19        |
| Palu                | 4554      | 2436      | 429        | 60.94     | 32.60     | 5.74        |
| Biak                | 4861      | 1768      | 243        | 70.45     | 25.63     | 3.52        |

Clouds are classified into four types based on the height of the cloud base (CBH) and the thickness of the cloud layer. Based on this classification, low-level clouds' occurrence is relatively higher than the occurrence of other cloud types. The lowest cloud appearance proportion value in Indonesia was observed at stations Surabaya (52.13%), Manado (49.82%), Ujung Pandang (47.77%) and Jakarta (47.71%) (Figure 1). These stations are located in areas that tend to be maritime. Relatively small cloud occurrence is observed for deep convective clouds with an occurrence percentage below 10% (Figure 1). However, these clouds contribute more to generate high rainfall. From the above discussion, it can be seen that the largest cloud distribution in Indonesia is low-level clouds and single-layer clouds.

![Figure 1](image-url)  
Figure 1: The percentage of occurrence of low, middle, high and deep convective clouds

3.2. Distribution of Rainfall in Indonesia
Rainfall in Indonesia is generally included in the monsoonal rainfall pattern. This monsoonal rainfall pattern is marked by one peak of the rainy season (unimodal), namely the November to March period (Nov-Des-Jan-Feb-Mar or NDJFM) where wet monsoons occur from the west, while the May to September period (May-Jun-Jul-Aug-Sep or MJJAS) occurs the dry southeast monsoon. Wet Monsoon (monthly rainfall above 150 mm) and Southeast Monsoon (monthly rainfall below 150 mm) [19].
Figure 2 shows the pattern of monthly average rainfall in Indonesia for all observation stations. In December-January-February (DJF) there was an increase in the average rainfall. January is the highest peak of the rainy season that occurs in several stations, especially Ujung Pandang Station with the largest rainfall value of 603.09 mm/month and November is also the peak of rainfall. Rainfall at Padang station is around 488.78 mm/month. Meanwhile, in the months of June-July-August (JJA) there was a decrease in the average rainfall at all observation stations. These results are consistent with research conducted by Adrian, 2003 [19].

The area of Indonesia is grouped into 3 rain areas with monsoonal, equatorial and local rainfall patterns [19]. Region A with a monsoonal pattern has one peak of rain during the DJF which is located in southern Indonesia from southern Sumatra to the island of Timor. Region B with an equatorial pattern with two peaks of rainfall (MAM and SON), is located in northwest Indonesia from north Sumatra to northwestern Kalimantan. The two peaks of rain occur in April (the first peak) with a value of 390.76 mm/month (Padang) and 240.24 mm/month in Medan, while in November (the second peak) with a rainfall value of 488.78 mm / month (Padang) and 255.48 mm / month (Medan) This is consistent with previous studies that the peak of rain in Padang city occurred in April and November [20]. Region C with a local pattern has a peak rainfall during JJA covering Maluku and northern Sulawesi. This area is included in Palu station with the peak of rainfall during JJA, encompasses Maluku and northern Sulawesi. This area is included in Palu station with the peak of rain in June with a rainfall value of 129.90 mm / month.

3.3. Relationship between cloud parameters and rainfall

| Observation Station | Low CT | Low CBH | Low Thickness | Middle CT | Middle CBH | Middle Thickness |
|---------------------|--------|---------|--------------|-----------|------------|-----------------|
| Padang              | 3.4    | 0.86    | 2.54         | 5.89      | 3.66       | 2.23            |
| Pangkal             | 2.83   | 0.99    | 1.84         | 5.38      | 3.49       | 1.89            |
| Pinang              | 2.95   | 1.05    | 1.9          | 5.52      | 3.49       | 1.89            |
| Medan               | 2.95   | 1.05    | 1.9          | 5.52      | 3.49       | 1.89            |
Observation Station  | Low CT | Low CBH | Low Thickness | Middle CT | Middle CBH | Middle Thickness
---|---|---|---|---|---|---
Surabaya  | 2.76 | 0.94 | 1.82 | 5.06 | 3.41 | 1.64
Jakarta  | 2.94 | 1.04 | 1.9 | 5.35 | 3.48 | 1.87
Manado  | 3.36 | 0.87 | 2.49 | 5.54 | 3.65 | 1.88
Ujung Pandang  | 2.95 | 0.91 | 2.04 | 5.46 | 3.62 | 1.84
Palu  | 2.76 | 1.05 | 1.71 | 5.15 | 3.49 | 1.65
Biak  | 3.08 | 0.85 | 2.23 | 3.69 | 2.37 | 7.35

Observation Station  | High CT | High CBH | High Thickness | Deep convective
---|---|---|---|---
Padang  | 7.59 | 6.33 | 1.26 | 8.14 | 0.76 | 7.38
Pangkal Pinang  | 7.73 | 6.53 | 1.2 | 8.44 | 0.86 | 7.58
Medan  | 7.46 | 6.32 | 1.14 | 8.25 | 0.92 | 7.33
Surabaya  | 7.85 | 6.52 | 1.34 | 8.54 | 0.92 | 7.33
Jakarta  | 7.7 | 6.55 | 1.15 | 8.26 | 0.89 | 7.36
Manado  | 7.56 | 6.44 | 1.12 | 8.34 | 0.76 | 7.58
Ujung Pandang  | 7.69 | 6.45 | 1.24 | 8.34 | 0.76 | 7.58
Palu  | 7.38 | 6.32 | 1.06 | 8.26 | 0.85 | 7.4
Biak  | 7.65 | 6.35 | 1.3 | 8.43 | 0.8 | 7.63

### Table 3. Occurrence Percentage of deep convective clouds during DJF, JJA, MAM, and SON

| Observation Station | DJF% | JJA% | MAM% | SON% |
|---|---|---|---|---|
| Padang  | 10.09 | 6.32 | 8.96 | 10.75 |
| Pangkal Pinang  | 4.65 | 3.28 | 2.97 | 2.07 |
| Medan  | 3.11 | 2.99 | 2.35 | 4.71 |
| Surabaya  | 7.69 | 1.92 | 5.87 | 3.98 |
| Jakarta  | 7.53 | 2.11 | 2.72 | 3.45 |
| Manado  | 8.79 | 10.15 | 10.26 | 8.14 |
| Ujung Pandang  | 10.87 | 5.16 | 7.85 | 3.89 |
| Palu  | 3.26 | 3.32 | 4.82 | 3.177 |
| Biak  | 8.53 | 10.06 | 9.14 | 7.23 |

In this study we focus more on deep convective cloud types, because these clouds contribute more to produce high rainfall because they have a thick thickness. This can be seen in Table 2, that cloud parameters for deep convective clouds in Indonesia are observed at nine observation stations that have a peak height of about ~ 8 km MSL, a cloud base height <1 km MSL so that the thickness of the layers obtained is around ~ 7 km. This thickness is much higher than the other three cloud types. Parameters of cloud height and cloud layer thickness are related to rainfall events, where clouds that have a high peak height with a thick layer thickness are clouds that produce rainfall with great intensity. Thinner clouds are most likely to occur with less rainfall, whereas thicker clouds are most likely to occur with heavy rainfall [9]. The appearance of this deep convective cloud in Indonesia is around 10%, its appearance is much larger than in other countries such as India, the appearance of which is around 1.1% [18].
Rain-producing clouds usually occur more frequently during the rainy season. Therefore, it is necessary to know the seasonal variations of these convective clouds. Table 3 shows the percentage of occurrence of deep convective clouds for each observation station in the DJF, JJA, MAM and SON. Two observation stations (Padang and Ujung Pandang) have a high contrast percentage of deep convective cloud appearance during the rainy season (DJF) and dry season (JJA). The occurrence of deep convective clouds at Padang station was 10.09% during the DJF and 6.32% during JJA. This percentage is also high at Ujung Pandang station, around 10.87% during DJF and 5.16 during JJA. This result is consistent with the highest peak rainfall values that occurred at the two stations, namely (603.09 mm / month) Ujung Pandang and (488.78 mm / month) Padang during the wet months (rainy season) (Figure 2). Thus, the difference in the vertical structure of clouds during the rainy and dry seasons indicates a strong relationship between the vertical structure of clouds and rainfall.

4. Conclusion
One-layer clouds' appearance is more common than other cloud layers, more than 60%. The dominance of single-layer clouds is consistent with research in other regions. However, the percentage of single layer clouds in Indonesia is higher than any other regions in the world at more than 60%. The increase in the average rainfall occurred during the months December-January-February (DJF). January is the highest peak of rainfall at Ujung Pandang station (603.09 mm / month) and November is the peak of rain at Padang station (488.78 mm / month). The decrease in the average rainfall occurred during June-July_Agustus (JJA). These results are consistent with previous studies. This increase and decrease in average rainfall is in line with the many deep convective cloud appearances observed during the DJF and JJA periods. The height of the deep convective cloud tops is ~8 km MSL, the cloud base height is <1 km MSL, so the thickness of the layers obtained is around ~7 km. Clouds with high peak height and thick layer thickness are clouds that produce large rainfall.

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