

Long-Term Change in Characteristics of Cloud Vertical Structures Over Sumatra from Radiosonde Observations

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ABSTRACT

Study on the vertical structure of cloud in Indonesia in terms of climate change is still very limited. We investigated the long-term change in characteristics of cloud vertical structures over Sumatra from three radiosonde observation stations in this work. The cloud base height (CBH), cloud top height (CT), and the number of cloud layers were retrieved using relative humidity (RH) profiles from radiosonde observation. The height of the cloud base is determined by taking the height of the layer with relative humidity (RH) value > 84% with at least a 3% jump in the RH from the ground level. Sumatra's most frequently observed cloud layer is a one-layer cloud with an average occurrence rate of > 60%, which is slightly larger than the one-layer cloud globally. The percentage of appearance values at the Padang station, Pangkal Pinang, and Medan are 63.58%, 69.50% and 66.05%. The appearance of low-level clouds also dominates in Sumatra compared to other cloud types. CT and CBH increase with the number of years including all seasons. This is in line with the increase in temperature in Indonesia reported by previous researchers. On the other hand, the clouds' thickness, especially for the cloud with one layer, varies from one location to another. The thickness of clouds decreases at Padang station and does not change at Pangkal Pinang and Medan stations.

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1. INTRODUCTION

Clouds influence the balance of energy radiation on earth through the process of absorption and reflection of sunlight entering the earth's atmosphere (Stephens et al., 2012; Zhou et al., 2016). The amount of radiant energy absorbed and reflected depends on the cloud type (Naud et al., 2016). Low clouds tend to cool the earth, and high clouds tend to heat the surface. Thus, clouds have an impact on the radiation balance on earth, and this role depends on the distribution of clouds and vertical cloud structures such as cloud top height (CT), cloud base height (CBH), cloud thickness, and the number of cloud layers (Li et al., 2016). Cloud characteristics, including cloud height, cloud cover and cloud morphology can change with climate change (Eastman and Warren, 2013).

Surface-based observations (Dong and Minnis, 2016) and satellites (Minnis and Harrison, 1984) are widely used to study cloud profiles, such as the CloudSat satellite and the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO). The CloudSat and CALIPSO have provided a new picture of the vertical profile of clouds. However, CloudSat has limitations in which this instrument cannot accurately identify high (thin) clouds (Marchand et al., 2008). Furthermore, considerable uncertainty of CBH values from CloudSat and CALIPSO data has also been reported (Zhang et al., 2017). More accurate CBH values can be obtained using surface-based cloud observation data such as cloud radar, lidar (Borg et al., 2011), and ceilometer (Martucci et al., 2010). Apart from the high accuracy in measuring CBH, this instrument has a continuous temporal coverage

(Sharma et al., 2016). However, observation of cloud height using a ceilometer is limited to an altitude of less than 4 km (Dai et al., 2016). The observation points of Lidar and Ceilometer is also are still limited in the world. The deficiencies of surface and satellite observations can be overcome using radiosondes.

A radiosonde is a set of flying balloons that are used to measure atmospheric parameters and send these observational data to receiving stations via specific radio frequencies. Radiosonde operates at a frequency of 433 MHz or 1680 MHz (Simanungkalit, 2018). Radiosondes can reach cloud layers to measure relative humidity, temperature, and pressure to estimate the vertical profile of the atmosphere, including clouds. Besides those parameters, radiosonde also can observe the wind speed and direction. More importantly, radiosondes can reach the atmospheric layer at an altitude of 30 km from the earth's surface. It is possible to retrieve CT, CBH and the number of cloud layers globally (Zhang et al., 2010).

Research on the vertical structure of clouds has been carried out in various countries worldwide with long-term use of radiosonde data (Wang and Rossow, 1995; 2000; Reddy et al., 2018). However, in Indonesia, this research is very limited. Research that has been done is limited to the spatial distribution of clouds from satellite observations (Marzuki et al., 2013; 2017). For two years, observation of the distribution of the vertical structure of clouds and aerosols using lidar Mie scattering has been carried out in Jakarta. They found the maximum value of CBH at an altitude of 5 km and have not reached the top of the cloud (Sugimoto et al., 2000). Therefore, further research was conducted on the vertical structure of the cloud. This study analyzes the characteristics of the vertical cloud structure in Sumatra as a result of climate change using radiosonde data ~30 years of observation. Radiosonde observations were carried out at three observation stations, namely Padang, Pangkal Pinang, and Medan.

2. METHOD

The data used in this study were radiosonde data managed by the University of Wyoming (<http://weather.uwyo.edu/upperair/sounding.html>). The radiosonde is launched twice per day, at 12:00 UTC and 00:00 UTC. In this study, the data of two observation periods are combined. Because we are also dealing with cloud vertical structure characteristics in terms of climate change, we have only used the Radiosonde station with the data availability of at least 30 years. Of the 15 stations in Sumatra, three stations meet this criterion. The location and specification of these stations are given in Figure 1 and Table 1, respectively. Retrieval of the vertical cloud structure from radiosonde data was carried out using brightness temperature data from the observation of Multifunctional Transport Satellites (MTSAT).

The cloud parameters were determined using the method proposed by Wang and Rossow (1995). CBH and CT are determined by taking the lowest and highest layers with relative humidity (RH) > 84%. RH profiles > 84% RH should be observed for at least four successive gate ranges with a 3% jump of RH in the basement layer. All radiosonde sounding profiles are not taken when the altitude is < 600 m above ground level (AGL). The difference between the base and the crest is defined as the thickness of the cloud.

After the parameters are determined, we calculate the proportion of cloud occurrences. The percentage of cloud occurrences is obtained from the number of occurrences of a cloud layer for ~ 30 years divided by the total cloud layer data at each observation station. Once the cloud vertical structure parameters such as CBH, CT, and the number of cloud layers were obtained, the clouds were grouped into four categories: low, middle, high, and deep convective clouds, following the method used by previous researchers (Lazarus et al., 2000; Zhang et al., 2010). Low-level clouds are defined as clouds with a thickness of < 6 km and CBH < 2 km. Furthermore, intermediate level clouds are assumed if CBH ranges from 2 km to 5 km. For CBH > 5 km, clouds are defined as high-level clouds. Finally, deep convective clouds are shown > 6 km thick and CBH < 2 km. Clouds are also grouped based on the season period December-January-February (DJF), June-July-August (JJA), September-October-November (SON), and March-April-May (MAM) to see seasonal cloud variations.

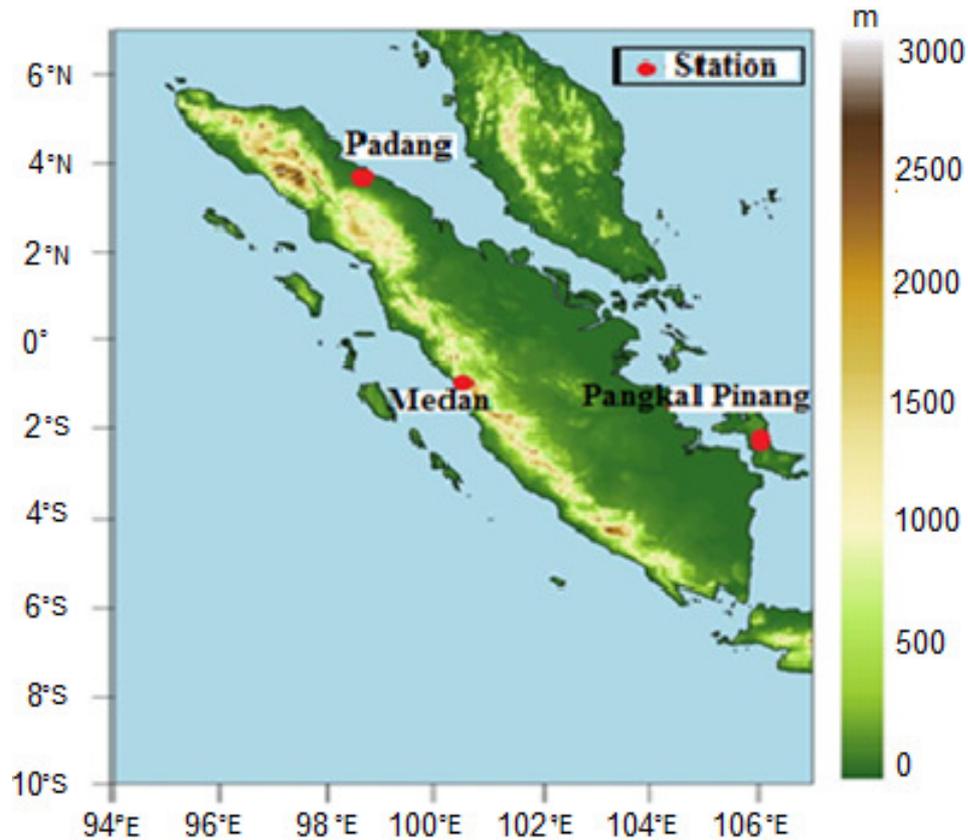


Figure.1 Location of radiosonde stations.

Table 1. Duration of radiosonde observation used in this study

| No | No station | Station ID | Station name | Latitude | Longitude | Observation year |
|----|------------|------------|----------------|----------|-----------|------------------|
| 1 | 96163 | WIMG | Padang | 0.88°S | 100.35 °W | 1988-2019 |
| 2 | 96035 | WIMM | Medan | 3.57°N | 98.68°W | 1975-2019 |
| 3 | 96237 | WIKK | Pangkal Pinang | 2.16°S | 106.13°W | 1985-2019 |

3. RESULTS AND DISCUSSION

3.1 Validation of Cloud from Radiosonde with MTSAT Data

Figure 2 shows the clouds detected by MTSAT and radiosonde over the Padang station (0,88°S 100,35°E). The range of brightness temperature for several weather conditions includes 60°C to 8°C (clear air), 8°C to 0°C (light cloudy), 0°C to -28°C (cloudy), -28°C to -56°C (thick cloudy), and -56°C to -100°C (very thick cloudy) (Gunawan, 2016). On April 13, 2019, at 00.00 UTC, clouds over Padang were observed at temperatures of 245 K to 240 K (-28°C to -33 °C) characterized by light blue contours (Figure 2a). This cloud is also observed by radiosonde. The RH value of 89% appears at an altitude of 4.2 km, with a maximum RH value of 100% at an altitude of 5.8 km (11% RH jump). This layer is observed until an altitude of 6 km (Figure 2b). From this comparison, it can be seen that cloud retrieval from radiosonde data can detect clouds observed by the MTSAT satellite correctly.

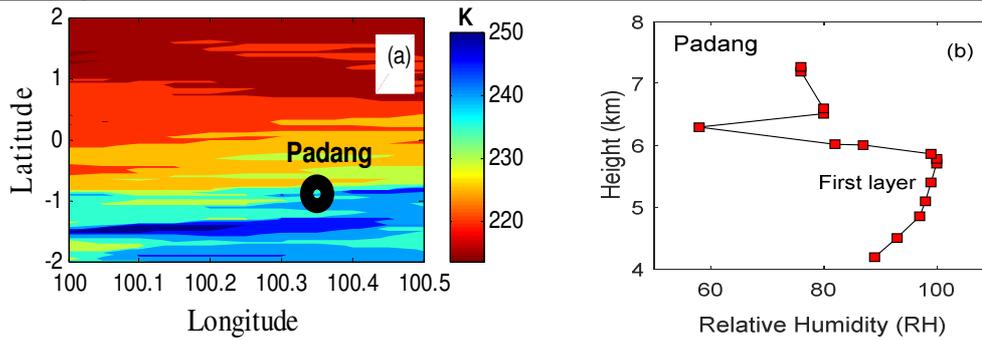


Figure 2. Cloud observed by (a) MTSAT satellites and (b) radiosonde at Padang station on April 13, 2019 at 00:00 UTC.

3.2 Distribution of Cloud Layers and Cloud Types

Figure 3a shows the distribution of the number of cloud layers from the three observation stations. One-layer, two-layer, three-layer, and four-layer clouds are the cloud layers observed in Sumatra. One-layer cloud is the cloud that appears most frequently, with an average occurrence percentage of > 60%, including 63.58% (Padang), 69.50% (Pangkal Pinang) and 66.05% (Medan) station. This value slightly exceeds the appearance of one layer cloud from another country.

In India, the percentage of one-layer clouds is around 40.80% (Reddy et al., 2018). Wang and Rossow (1995) and Wang et al. (2000) analyzed global radiosonde observations and found the appearance of a one-layer cloud of 44% and 58%, respectively. These stations are located in areas with relatively small landmass and close to the ocean. Maritime-like clouds may be somewhat dominant at these stations. These results are consistent with previous researchers who also found high cloud incidence in oceanic regions, the proportion of one-layer clouds around 53% (Warren et al., 1988; Lazaros et al., 2017). The percentage of occurrence of low, middle, high, and deep convective clouds is shown in Figure 3b. The clouds that occur most frequently at each station are low-level clouds. The largest percentage of low-level clouds in Sumatra is observed at Padang station (48.36%). The observation of low-level cloud structure is in line with previous research by stating that the abundance of low level clouds over the ocean is almost three times greater than that on land (Chepfer et al., 2010; King et al., 2013). An upstream current is lower in the oceanic convective system so that the shallow clouds are more dominant in this area (Rosenfeld and Ulbrich, 2003; Marzuki et al., 2013; 2018a; 2018b).

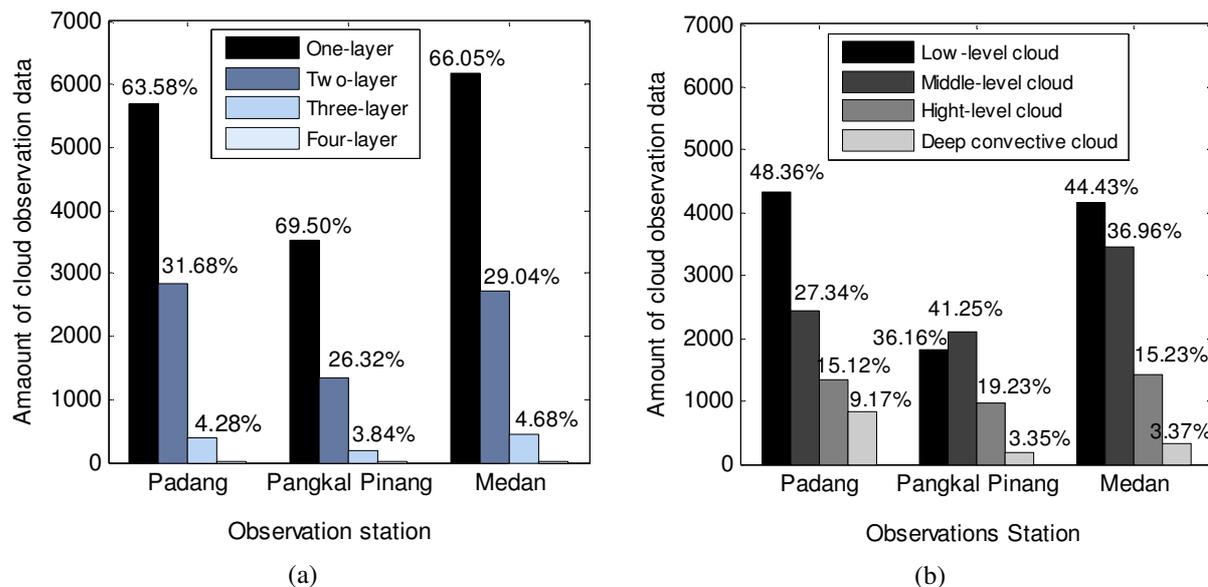


Figure 3. Distribution of observation data (a) based on the number of cloud layers (b) low-level clouds, middle-level clouds, high-level clouds, deep convective clouds and the percentage of occurrence

3.3 Seasonal Variations in Cloud Vertical Structure

Figure 4 shows the percentage of cloud layer occurrences for each observation station during DJF, JJA, MAM and SON. In general, one cloud layer is dominant in all seasons. However, the JJA period (dry season) has a larger percentage of cloud appearance than other seasons, ranging from 65% -71%. The station with the highest percentage is in Pangkal Pinang, with a value of 71.02%. This period coincides with monsoon rainfall patterns, especially the dry southeast monsoon (Aldian and Susanto, 2003). Thus, although many clouds are observed at the stations during JJA, it does not produce heavy rain as they are mostly low level clouds (Lismalini et al., 2020b). During the DJF season, the percentage of cloud layer appearance was relatively large, with the stations of Padang 63.48%, Pangkal Pinang 68.78% and Medan 70.24%. For the MAM and SON period, the highest percentage was also found at Pangkal Pinang station with values of 69.55% and 68.94%. A high percentage of two-layer clouds are observed for all stations.

The four cloud types classified based on CBH and the cloud layer's thickness is shown in Figure 5. Low-level clouds are more dominant in appearance than other cloud types in all seasons (Figure 5a). However, of the four seasons, the JJA season (dry season) has a more dominant percentage. The minimum appearance of low-level clouds (36.16%) occurred at Pangkal Pinang station (Figure 3b). It is consistent with low rainfall throughout the year (Marzuki et al., 2021). The deep convective cloud's appearance is relatively smaller than other clouds, i.e., about 11% (Figure 5d). However, these clouds contribute more to produce high rainfall. Therefore, the deep convective cloud's seasonal variation is more robust than other clouds, which is in line with the rainy season's occurrence (Lismalini et al., 2020b). The occurrence of deep convective clouds at Padang station is 10.09% during DJF.

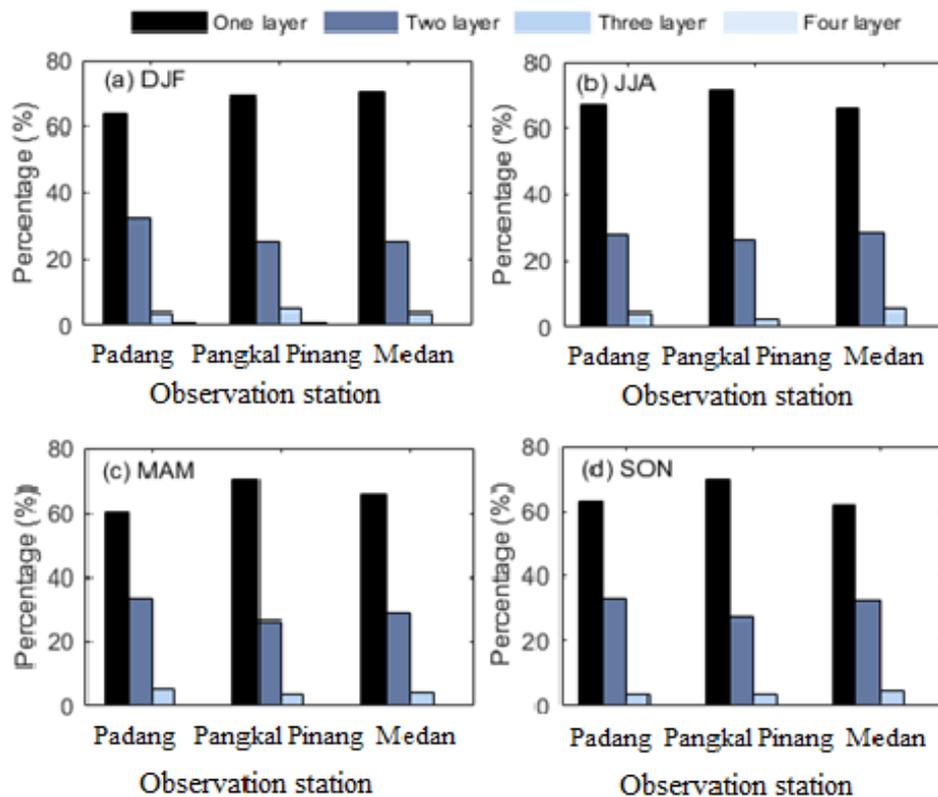


Figure 4. Occurrence Percentage of one-, two-, three-layer and four-layer clouds during (a) DJF, (b) JJA, (c) MAM, and (d) SON

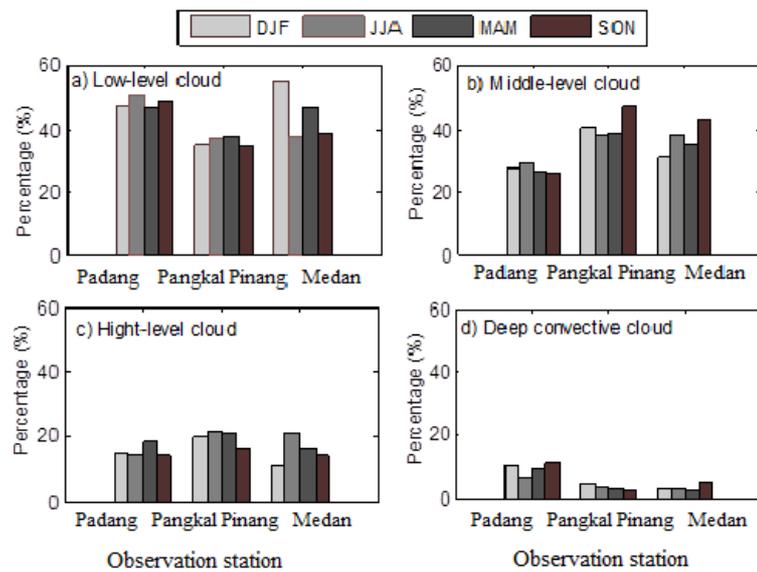


Figure. 5 Occurrence percentage of (a) low-level cloud, (b) middle-level cloud, (c) high-level cloud and (d) deep convective cloud for each season.

3.4 Long-Term Change in Cloud Parameters

The long-term changes of the one-layer cloud and the two-layer cloud at the Padang station are shown in Figure 6 and Figure 7. CT and CBH have increased over the past 30 years in each cloud layer. The highest increase occurred in one-layer clouds with a value of 0.04 km/year (Figure 6a and Figure 6b), with the highest correlation coefficient in CBH ($R^2 = 0.25$). This study's result is consistent with Chernykh et al. (2001) who reported an increase in CT globally, including the Asian continent. However, in contrast to the cloud thickness trend at Padang station, there was a relatively small decrease in each cloud layer. Figure 8 and Figure 9 show the observed trend of cloud parameters at Pangkal Pinang station. Cloud parameters have increased in each cloud layer (CT, CBH and cloud thickness). Except for cloud layer thickness for single-layer clouds has not changed for ~ 30 years. The value of the increase is about 0.05 km/year. The increase in CT and CBH also occurred at Medan stations. The value of the increase is smaller than the Padang and Pangkal Pinang stations. The increase in CT and CBH was about 0.02 km/year and 0.01 km/year, respectively (Figure 10a and Figure 10b). The same conditions are seen in the two-layer cloud. However, the cloud layer thickness trend did not experience, as seen in Figure 11c and Figure 11f.

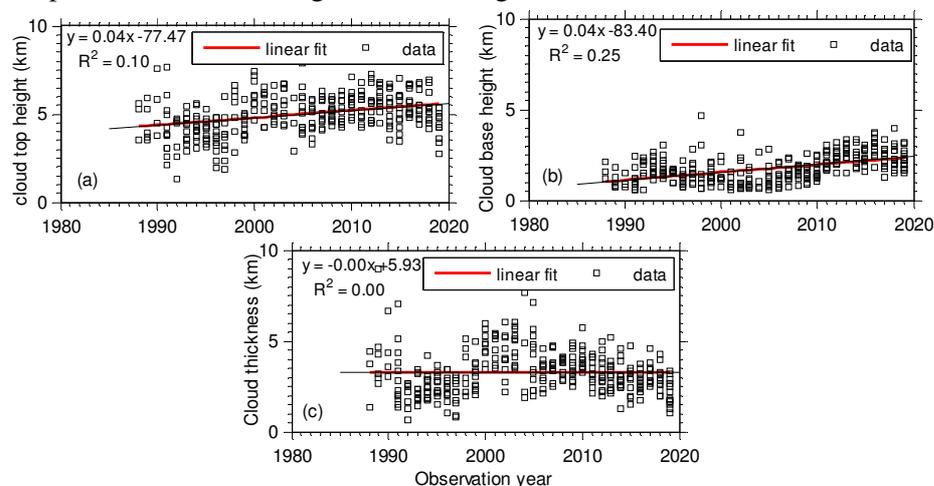


Figure 6. Time series of cloud top height (a), cloud base height (b) and cloud thickness (c) for one-layer cloud at Padang station

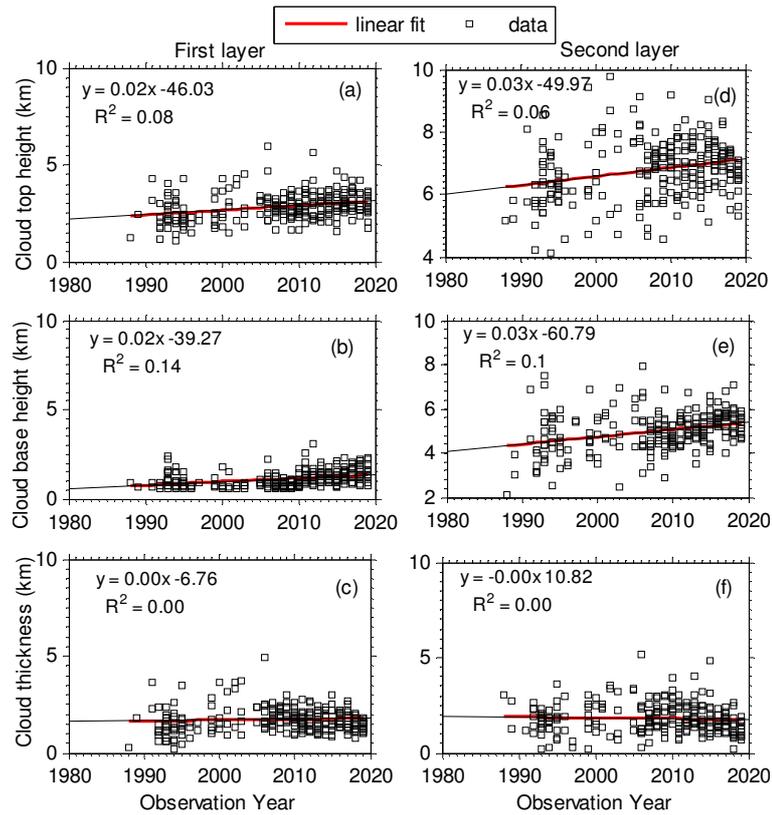


Figure 7. Time series of cloud top height (a and d), cloud base height (b and e) and cloud thickness (c and f) for two layer clouds at Padang station

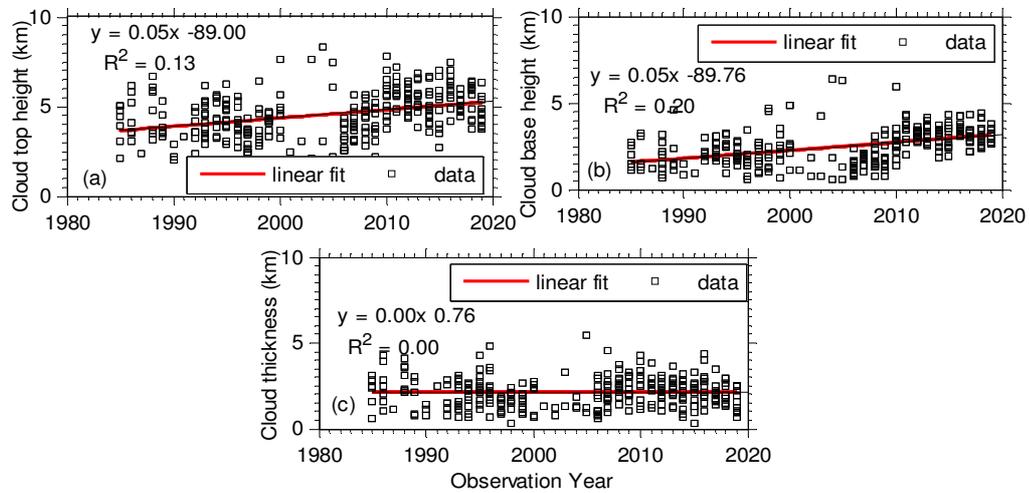


Figure 8. Time series of cloud top height (a), cloud base height (b) and cloud thickness (c) for one-layer cloud at Pangkal Pinang station

In general the CT and CBH have increased over the last 30 years from the three observation stations in Sumatra. These results are consistent with previous studies (Chernykh et al., 2001) and in accordance with the results reported by Lismalini et al. (2020a) regarding increased CT and CBH. The increase in the cloud height parameter is related to the surface temperature. Increasing earth's surface temperature will increase the height of the clouds because the convection process is closely related to temperature. The increase in surface temperature in Indonesia has been reported by several previous researchers (Susandi, 2004). The trend in cloud thickness varies for the three stations. However, if it is seen from the number of cloud layers at each station, it can be seen that the increasing number of cloud layers and the value of the cloud thickness will decrease.

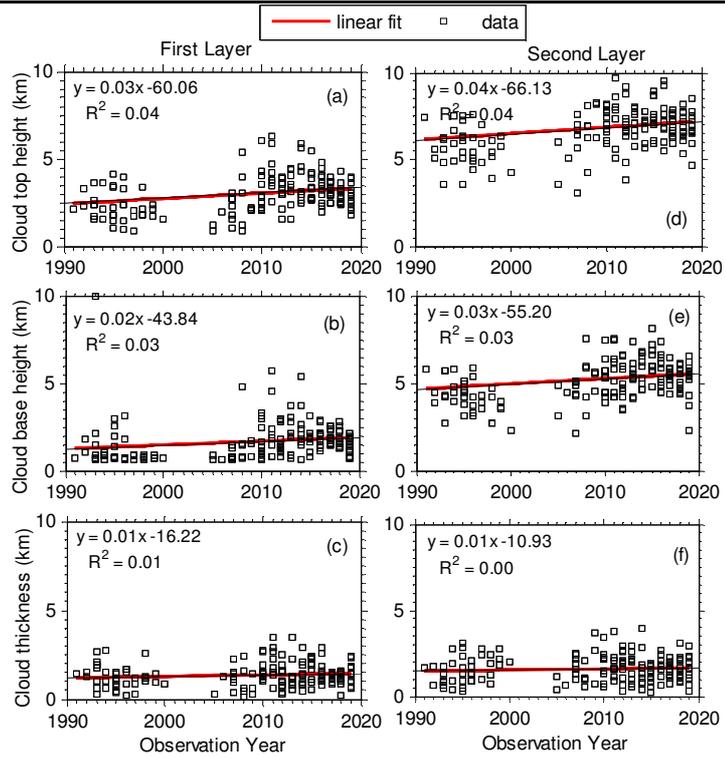


Figure 9. Time series of cloud top height (a and d), cloud base height (b and e) and cloud thickness (c and f) for two-layer clouds at Pangkal Pinang station

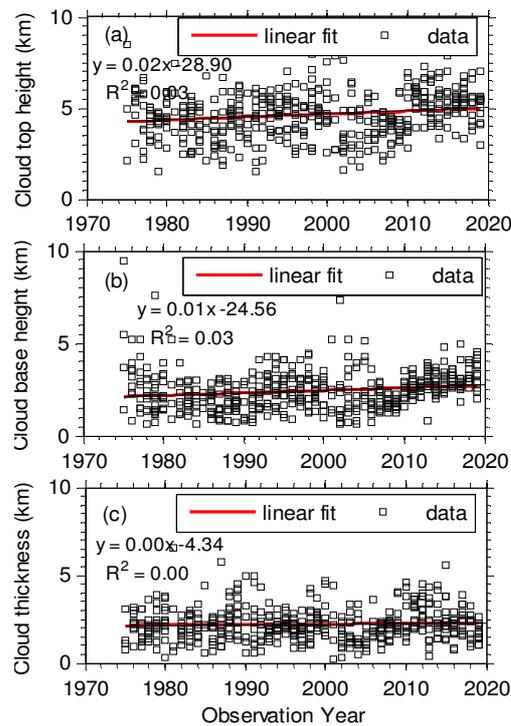


Figure 10. Time series of cloud top height (a), cloud base height (b) and cloud thickness (c) for one-layer cloud at Medan station

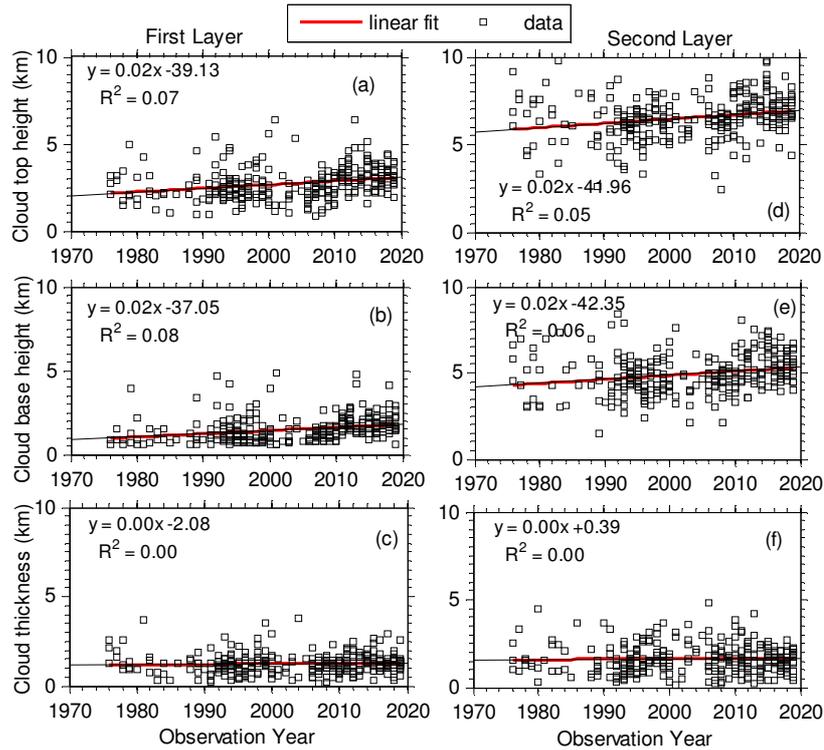


Figure 11. Time series of cloud top height (a and d), cloud base height (b and e) and cloud thickness (c and f) for two-layer clouds at Medan station

The time series of long-term changes in cloud parameters in a one-layer cloud during the DJF, JJA, MAM and SON seasons in Sumatra is shown in Figure 12. There has generally been an increase in CT and CBH across all seasons over the past 30 years. The increase in CT and CBH was relatively small with a low correlation coefficient, as shown in Table 1. The Largest increase was at Padang stations around 0.05 km/year with the highest correlation coefficient ($R^2 = 0.03$) during the DJF season (Table 2). However, it differs from the trend of cloud layer thickness in each season. During the JJA and MAM seasons, there was a decrease in thickness at Padang stations. This can be seen from the linear regression values in Table 3 and Table 4. During the JJA and SON seasons there was also a decrease in thickness at the Pangkal Pinang station, this is shown in Table 3 and Table 5.

Table 2. Linear regression equation of one-layer cloud for DJF period

| Station name | Cloud top height | Cloud base height | Cloud thickness |
|----------------|----------------------|---------------------|---------------------|
| Padang | $y = 0.05x - 103.28$ | $y = 0.05x - 91.48$ | $y = 0.01x - 11.80$ |
| | $R^2 = 0.19$ | $R^2 = 0.33$ | $R^2 = 0.02$ |
| Pangkal Pinang | $y = 0.06x - 118.92$ | $y = 0.05x - 98.75$ | $y = 0.01x - 20.18$ |
| | $R^2 = 0.20$ | $R^2 = 0.28$ | $R^2 = 0.02$ |
| Medan | $y = 0.01x - 19.32$ | $y = 0.01x - 24.50$ | $y = -0.00x + 5.18$ |
| | $R^2 = 0.01$ | $R^2 = 0.03$ | $R^2 = 0.00$ |

Table 3. Linear regression equation of one-layer cloud for JJA period

| Station name | Cloud top height | Cloud base height | Cloud thickness |
|----------------|---------------------|----------------------|----------------------|
| Padang | $y = 0.03x - 45.77$ | $y = 0.04x - 80.30$ | $y = -0.01x + 34.53$ |
| | $R^2 = 0.03$ | $R^2 = 0.19$ | $R^2 = 0.01$ |
| Pangkal Pinang | $y = 0.03x - 46.95$ | $y = 0.04x - 72.53$ | $y = -0.01x + 25.57$ |
| | $R^2 = 0.06$ | $R^2 = 0.13$ | $R^2 = 0.02$ |
| Medan | $y = 0.01x - 17.46$ | $y = 0.008x - 12.83$ | $y = 0.00x - 4.63$ |
| | $R^2 = 0.01$ | $R^2 = 0.01$ | $R^2 = 0.00$ |

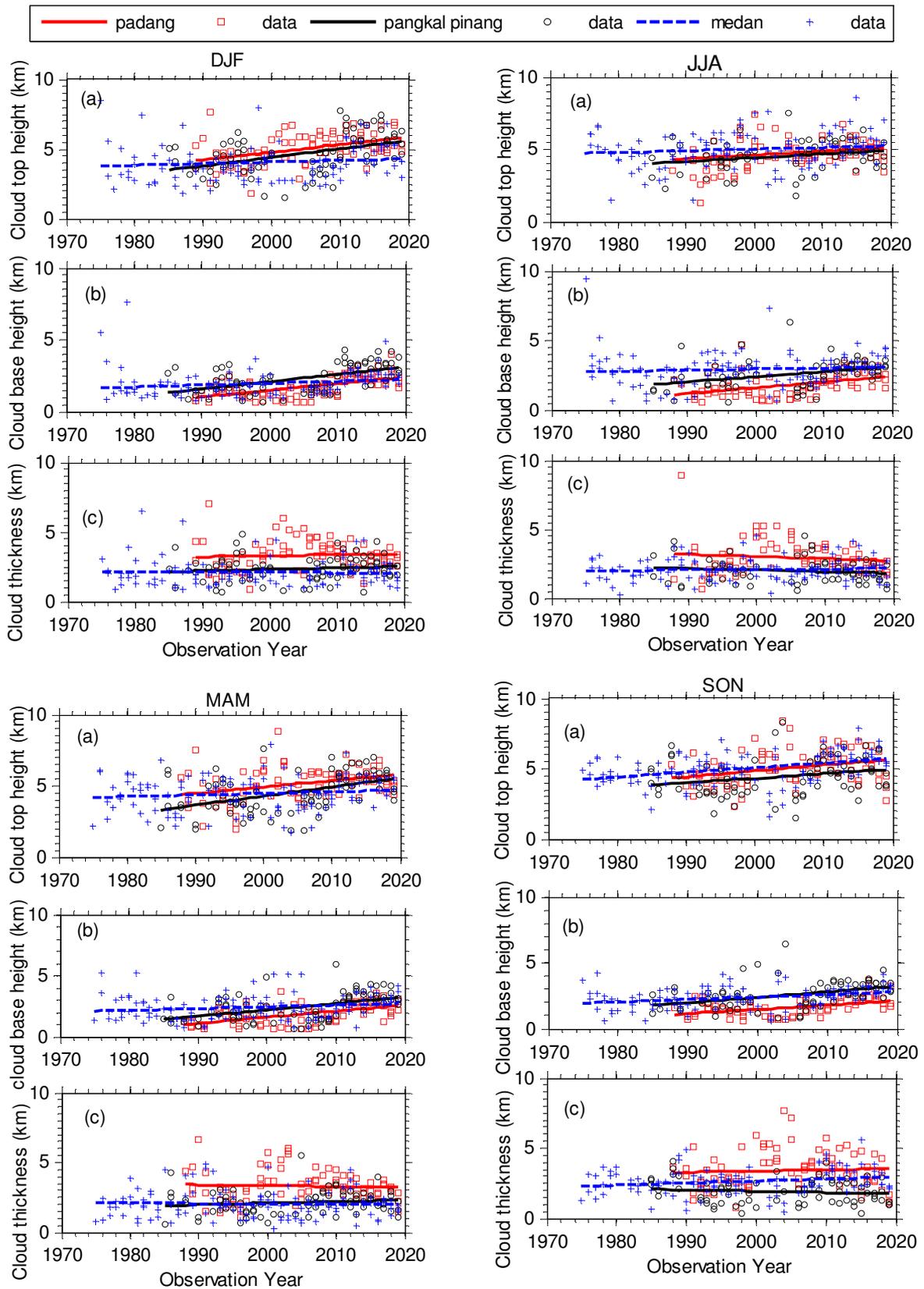


Figure 12. Time series of cloud top height (a), cloud base height (b) and cloud thickness (c) for one-layer cloud during DJF,JJA, MAM and SON periods

Table 4. Linear regression equation of one-layer cloud for MAM period

| Station name | Cloud top height | Cloud base height | Cloud thickness |
|----------------|----------------------------------|------------------------------------|-----------------------------------|
| Padang | $y=0.04x -83.29$ $R^2=0.11$ | $y=0.05x -98.27$ $R^2= 0.25$ | $y= -0.00 x 14.98$ $R^2= 0.00$ |
| Pangkal Pinang | $y= 0.06x-124.82$ $R^2= 0.21$ | $y = 0.05x -103.55$ $R^2= 0.22$ | $y = 0.01x -21.27$ $R^2= 0.02$ |
| Medan | $y = 0.01x -18.10$ $R^2=0.01$ | $y = 0.01x -24.87$ $R^2= 0.03$ | $y = -0.00x 6.76$ $R^2= 0.00$ |

Table 5. Linear regression equation of one-layer cloud for SON period

| Station name | Cloud top height | Cloud base height | Cloud thickness |
|----------------|-----------------------------------|---------------------------------|-----------------------------------|
| Padang | $y=0.04x -78.43$ $R^2=0.10$ | $y=0.03x -64.06$ $R^2=0.21$ | $y=0.01x -14.37$ $R^2= 0.00$ |
| Pangkal Pinang | $y = 0.03 x-60.57$ $R^2= 0.06$ | $y=0.04x -80.81$ $R^2= 0.18$ | $y = -0.01x 20.24$ $R^2= 0.01$ |
| Medan | $y = 0.03x -61.72$ $R^2=0.15$ | $y=0.02x -34.87$ $R^2=0.09$ | $y = 0.01x -26.85$ $R^2= 0.05$ |

4. CONCLUSION

The vertical structure of clouds in Sumatra shows an increase in CT and CBH over time. One-layer cloud's appearance is more common than other cloud layers, more than 60%. The dominance of one-layer clouds is consistent with some previous studies in other regions. However, the thickness of one-layer clouds varies from one location to another. The clouds' thickness decreases at Padang station and does not change at Pangkal Pinang and Medan stations. We also found that cloud thickness decreases as the number of cloud layers increase. The thickest cloud is observed in a one-layer cloud. The vertical structure of clouds is influenced by the seasons. Seasonal variations in the vertical cloud structure in Sumatra also indicate an increasing trend in the height of CT and CBH in all-season periods. The increase in cloud height parameters in this study is in line with the increase in Indonesia's surface temperature every year reported by several previous researchers. This study provides additional evidence about the impact of climate change on the vertical structure of clouds.

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