*Article*

# Assessment of aerosol-cloud-rainfall interactions in Northern Thailand

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**Abstract**

Biomass burning in the northern Thailand probably provides strong input of aerosols into the atmosphere, with potential effects on cloud and rainfall, over an entire burning season. This research was focus on effect of biomass burning aerosols on clouds and rainfall using multiple regression analysis and AOT for indicating aerosol concentrations from satellite MODIS (Terra / Aqua) and AERONET station since 2003-2012. The results indicated that average AOT of the Northern Thailand showed the highest value in pre-monsoon season especially in March with 0.5 unit less and decreased in June to July. It corresponded with hotspot data were mostly occurring in pre-monsoon season. Furthermore, almost all of the aerosols that were found during monsoon season as the big particles, caused by salt spray combine with water vapor. In the other hand, almost all of the aerosols during pre-monsoon were the small particles which come from the black carbon caused by biomass burning. There was high positive relationship with rainfall with cloud water content (CWC) and cloud fraction (CF), but it was found that were negative relationship with aerosol optical thickness (AOT) and hotspot (HP). There was moderate relationship between rainfall amount with AOT, cloud fraction (CF), cloud water content (CWC) and hotspot (HP) in all provinces of the northern Thailand. It was noticed that in any year there were the high biomass burning aerosols which caused rain later than usual about 1-2 months.

**Keywords** aerosols; AOT; cloud; rainfall; northern Thailand.

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## 1 Introduction

Aerosols actually act as cloud condensation nuclei (CCN) for cloud water droplets. The changes in aerosol concentrations have been observed as having significant impacts on the corresponding cloud properties (Ackerman et al., 2000; Rosenfeld, 2000; Andreae et al., 2004; Kaufman et al., 2005). An increase in aerosol concentration may lead to an increase in CCN, with an associated decrease in cloud droplet size for a given cloud liquid water content (Kaufman et al., 1997; Ramanathan et al., 2001). As mentioned (Rogers and Yau, 1989), clouds that form in air containing relatively low concentrations of CCN tend to have a broader droplet size distribution and a few large drops. Provided the latter drops are large enough (diameter $\gtrsim$ 40 μm) they can grow by collision-coalescence to form raindrops. It is for this reason that marine clouds tend to precipitate more efficiently than continental clouds. This is the theoretical basis for attempts to increase precipitation by seeding with large hygroscopic nuclei, which can provide the seeds upon which precipitable particles can grow. Smaller droplet sizes may then lead to a reduction in precipitation efficiency and an increase in cloud lifetimes (Rosenfeld, 1999, 2000). However, these effects are highly dependent on the aerosol concentration, aerosol species, and the meteorological conditions.

In Thailand, there have been more aerosols emissions to atmosphere found in each region and their effects on livelihood of people, particularly on cloud and rainfall. Hence, the different sources of aerosol such as biomass burning, soot and salt from sea spray caused different effects on cloud and rainfall characteristics. It is known that rainfall play essential role on agriculture and industry of Thailand. Aerosols may disperse rainfall and caused drought in some area of Thailand. Recently, it is still needed to clarify the effects of aerosols on clouds and rainfall. Consequently, the objectives of this paper are an attempt to particularly explain the spatial and temporal aerosol characteristics and analyze trend of temporal change on cloud and rainfall characteristics in Northern Thailand using observed by MODIS data. The specific objectives are following as (1) To investigate the spatial and temporal aerosol characteristics in northern Thailand (2) To detect observational evidence of aerosol effects on the spatial and temporal cloud and rainfall characteristics in northern Thailand (3) To formulate numerical relationships between aerosols with cloud and rainfall characteristics in northern Thailand.

## 2 Study area and Methodology

### 2.1 Study site

The upper northern Thailand was selected as the study area which had high the aerosol source emissions from forest fires and biomasses burning from agriculture area leading to produce smog problem during the past 5-10 years. Forest fire in this area constantly increased, especially pre-monsoon season or summer season, a cause of changing in the cloud physics and rainfall. This research covered 9 provinces covering Mae Hong Son, Chiang Mai, Chiang Rai, Lamphun, Lampang, Phayao, Phrae, Nan and Uttaradit. The area has co-ordinates with latitude, 17.5° to 20 ° N and longitude 98° to 101° E.

### 2.2 Data collection

2.2.1 Aerosol Optical Thickness (AOT) and fire count (hotspot numbers) were collected from Terra/Aqua MODIS and fire count activity information. The collected data were used to study the variability of aerosol loading in relation with the enhanced pre-monsoon biomass burning activity as that employed by Levy et al. (2007). Globally gridded daily and monthly mean MODIS products, with spatial resolution of were obtained for the period 2003-2012 from the NASA LAADS web portal.

2.2.2 Aerosol particles sizes from The Aerosol Robotic NETwork stations (AERONET) at Chiang Mai during year 2007 to 2012.

2.2.3 Daily and monthly cloud fraction (CF), cloud water content (CWC) and rainfall amount (RF) from TRMM data during year 2003 to 2012.

2.2.4 Daily particle Matter ($PM_{10}$) from Air and Noise pollution monitoring stations of from Pollution Control Department during year 2005 to 2012.

**2.3 Analysis data**

2.3.1 To determine temporal variation of aerosol using time series analysis. They were shown in monthly variations and seasonal variations were winter season (Nov-Jan), pre-monsoon season (Feb-Apr) and rainy season (May-Oct).

2.3.2 Two modes of aerosol size (< 1 micron as fine mode and > 1 micron as coarse mode) were analyzed determining aerosol particles size distribution using data collected from AERONET station.

2.3.3 To analyzed spatial and temporal aerosols characteristics from MODIS data (Terra/Aqua) using aerosol parameters to indicate aerosol concentration was Aerosol Optical Thickness (AOT).

Fire counts or Hotspot number from MODIS data during 2003 to 2012 were used for identifying amount and location of forest fire or biomass burning area.

2.3.4 Seasonal variation of rainfall and cloud water content (CWC) and cloud fraction (CF) derived from TRMM satellite data during year 2003 to 2012 were analyzed into 2 patterns, (1) Normal day (non-hazy day) and (2) burning day (Hazy day). Normal day (non-hazy day) was no has hotspot and $PM_{10}$ less than 120 $\mu g/m^3$ but burning day (hazy day) was defined by Hotspot day and $PM_{10}$ data (> 120 $\mu g/m^3$).

2.3.5 Relationships between aerosol, cloud and rainfall for determining suitable model using multiple correlations and multiple regression analysis as following are

$$R = f\{AOT, APS, Hot, CF, CWC\}$$

where AOT = Aerosol Optical Thickness (unitless)

APS = aerosol particle size (µm)

R = rainfall amount (mm)

Hot = hot spot (point)

CF = cloud fraction (unitless)

CWC = cloud water content ($g/cm^2$)

## 3 Results and Discussion

### 3.1 Spatial and seasonal variation of aerosols in the upper Northern Thailand

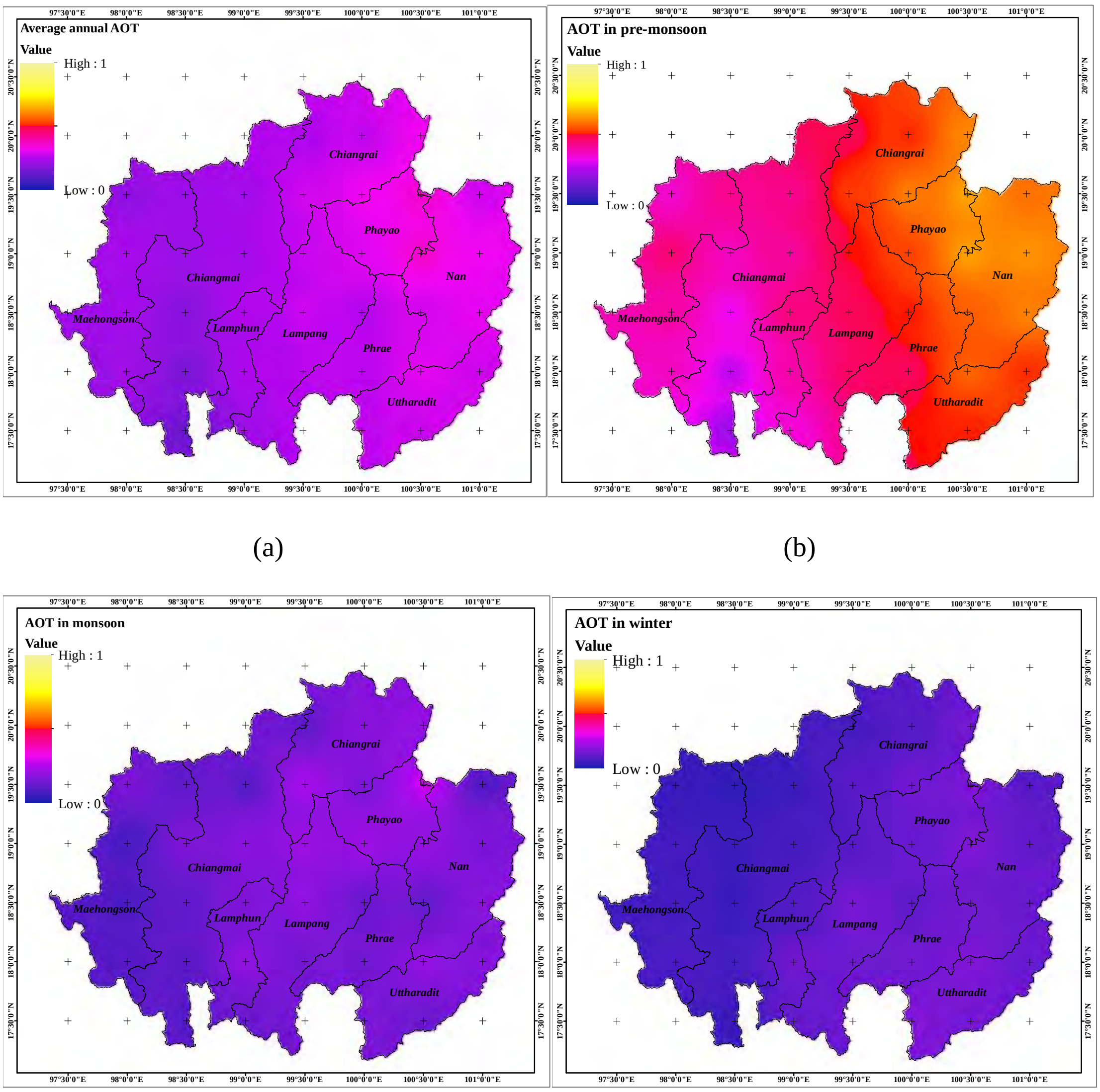
This result was separated into 2 parts were 1) variation of aerosol in different areas and 2) variation of aerosol in different seasons. The details are following;

3.1.1 Spatial variation of aerosols in the upper Northern Thailand

The spatial distribution of monthly mean AOT has been demonstrated for the period from 2003 to 2012 (Table 1, Fig. 1). The average annual AOTs of Northern Thailand were about 0.18-0.32 which implies that moderate aerosol concentration. In March, almost all provinces in Northern Thailand are found the high AOT (0.63) especially at Chiang Rai showed the highest AOT in Table 1 (0.79). The high AOT value (>0.4) are found over the northern areas by caused intense anthropogenic activity and burning areas.

**Table 1** Average monthly AOT in Northern Thailand (during year 2003 to 2012).

| Provinces | Average monthly AOT (during 2003 to 2012) | | | | | | | | | | | | Average Annual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | |
| Mae Hong Son | 0.07 | 0.16 | 0.50 | 0.50 | 0.22 | 0.21 | 0.11 | 0.14 | 0.20 | 0.15 | 0.06 | 0.07 | 0.20 |
| Chiang Mai | 0.05 | 0.15 | 0.47 | 0.46 | 0.23 | 0.28 | 0.00 | 0.10 | 0.22 | 0.14 | 0.05 | 0.07 | 0.18 |
| Lamphun | 0.12 | 0.23 | 0.52 | 0.51 | 0.25 | 0.30 | 0.08 | 0.12 | 0.22 | 0.18 | 0.10 | 0.13 | 0.23 |
| Chiang Rai | 0.14 | 0.36 | 0.79 | 0.65 | 0.25 | 0.10 | 0.21 | 0.06 | 0.17 | 0.21 | 0.11 | 0.14 | 0.27 |
| Lampang | 0.19 | 0.42 | 0.66 | 0.50 | 0.21 | 0.22 | 0.06 | 0.13 | 0.20 | 0.23 | 0.13 | 0.15 | 0.26 |
| Phayao | 0.12 | 0.28 | 0.77 | 0.64 | 0.25 | 0.22 | 0.12 | 0.21 | 0.20 | 0.20 | 0.11 | 0.14 | 0.27 |
| Phrae | 0.15 | 0.34 | 0.77 | 0.67 | 0.28 | 0.25 | 0.32 | 0.28 | 0.26 | 0.24 | 0.13 | 0.16 | 0.32 |
| Nan | 0.13 | 0.30 | 0.62 | 0.55 | 0.22 | 0.24 | 0.08 | 0.10 | 0.28 | 0.22 | 0.11 | 0.14 | 0.25 |
| Uttaradit | 0.17 | 0.35 | 0.57 | 0.51 | 0.18 | 0.23 | 0.04 | 0.13 | 0.12 | 0.17 | 0.11 | 0.15 | 0.23 |
| Mean of Northern Thailand | 0.13 | 0.29 | 0.63 | 0.55 | 0.23 | 0.23 | 0.11 | 0.14 | 0.21 | 0.19 | 0.10 | 0.13 | 0.25 |




(a) (b)

(c) (d)

**Fig. 1** Distribution of average Aerosol Optical Thickness (AOT) in Northern Thailand during 2003-2012 (a) annual AOT (b) AOT in pre-monsoon (c) AOT in monsoon and (d) AOT in winter.

3.1.2 Seasonal variation of aerosols in the Upper Northern Thailand

Seasonal variations of AOTs were shown in Table 2. The mean, maximum and minimum AOT during 2003 to 2012 were calculated as shown in Table 1. Table 2 was showed that mean AOT was highest during pre-monsoon season (February to April) are at about 0.5 especially in march over Chiang Rai, Phayao and Phrae. It was noticed that during this period the low pressure over the upper northern Thailand lifted the warm air masses above the Earth's surface. Aerosol particles were taken up in the low atmosphere causing haze. Aerosol concentrations during the pre-monsoon season (March to April) are typically at peak associated with biomass burning activity and contribute significantly to the regional emissions (Carmichael et al., 2003; Janjai et al., 2009; Streets et al., 2009). The seasonal emissions peak occurs prior to the onset of the Asian summer monsoon rains and is prevalent over the forested regions of the peninsula including Myanmar and northern Thailand. Smoke plumes due to biomass burning, accompanied by anthropogenic emissions, result in dense haze conditions, with episodic pollution levels at surface (e.g., $PM_{10}$, Total Suspended Particulate, etc.) far exceeding the regional air quality standards during the pre-monsoon season (Chew et al., 2008; Pengchai et al., 2009). In addition to air quality effects, aerosols from this region, mostly fine-mode smoke plumes, have been shown to have potential climate impacts by altering cloud microphysics (Ramanathan et al., 2001) and perturbing regional radiation budget (Hsu et al., 2003) during pre-monsoon season. In rainy season (May to October), mean AOT value was less at about 0.2 because it was washed out by rain (Table 2). The annual average AOT indicated at about 0.1 in the winter (November to January).

**Table 2** Seasonal average AOT in upper Northern Thailand (during 2003 to 2012).

| | Pre-monsoon (Feb-Apr) | | | Monsoon (May-Oct) | | | Winter (Nov-Jan) | | |
|---|---|---|---|---|---|---|---|---|---|
| Provinces | Mean | Max | Min | Mean | Max | Min | Mean | Max | Min |
| Mae Hong Son | 0.387 | 0.531 | 0.206 | 0.173 | 0.312 | 0.069 | 0.066 | 0.111 | 0.025 |
| Chiang Mai | 0.356 | 0.481 | 0.182 | 0.161 | 0.299 | 0.063 | 0.059 | 0.108 | 0.014 |
| Lamphun | 0.421 | 0.612 | 0.211 | 0.193 | 0.364 | 0.044 | 0.119 | 0.201 | 0.045 |
| Chiang Rai | 0.604 | 0.790 | 0.297 | 0.167 | 0.340 | 0.059 | 0.129 | 0.197 | 0.068 |
| Lampang | 0.526 | 0.700 | 0.298 | 0.175 | 0.333 | 0.051 | 0.154 | 0.246 | 0.080 |
| Phayao | 0.563 | 0.765 | 0.311 | 0.202 | 0.344 | 0.072 | 0.123 | 0.202 | 0.045 |
| Phrae | 0.591 | 0.776 | 0.327 | 0.273 | 0.527 | 0.104 | 0.147 | 0.216 | 0.073 |
| Nan | 0.490 | 0.653 | 0.269 | 0.190 | 0.354 | 0.069 | 0.127 | 0.208 | 0.053 |
| Uttaradit | 0.476 | 0.622 | 0.327 | 0.143 | 0.325 | 0.028 | 0.143 | 0.241 | 0.051 |
| Mean of Northern Thailand | 0.491 | 0.659 | 0.270 | 0.186 | 0.356 | 0.062 | 0.118 | 0.192 | 0.050 |

3.1.3 Aerosol particle size distribution

Analysis of aerosols size distribution was used ground based data of AERONET station at Chiang Mai since year 2007 to 2012. Fig. 2 shows that almost all of total Aerosol Optical Depth (Total AOD) in pre-monsoon are the small size of aerosol (Fine mode) but in rainy season almost all of aerosol in the atmosphere are big size of aerosol (Coarse Mode). So the small aerosol particles played more influence in pre-monsoon than the big size of aerosol particles (Table 3).

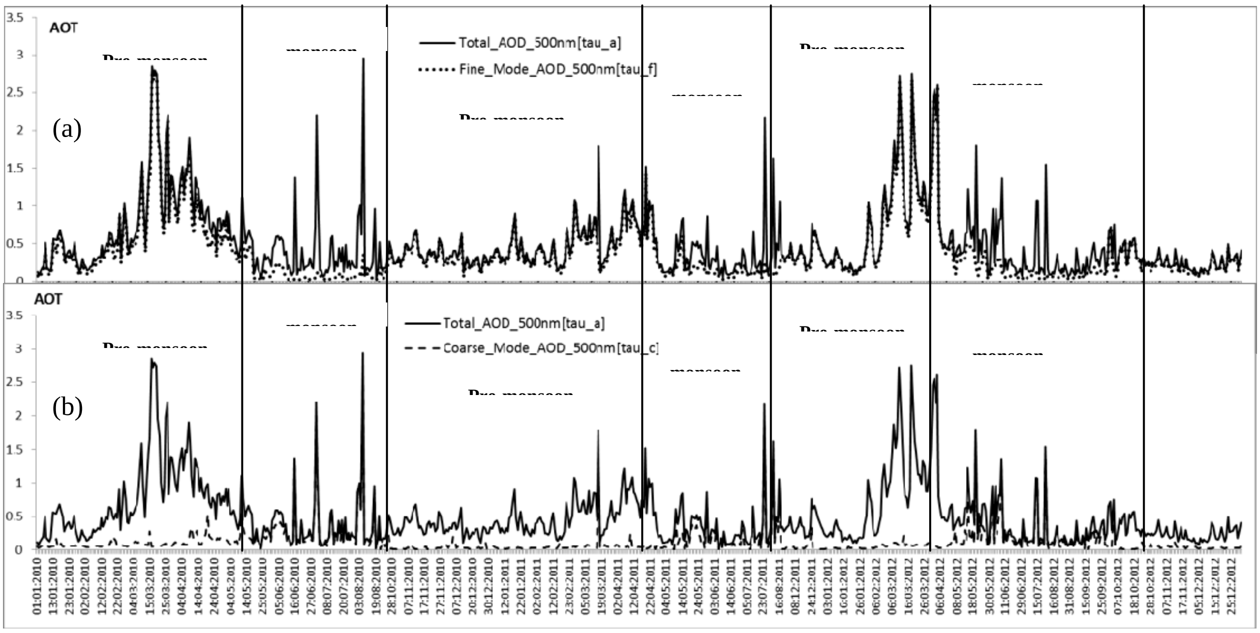


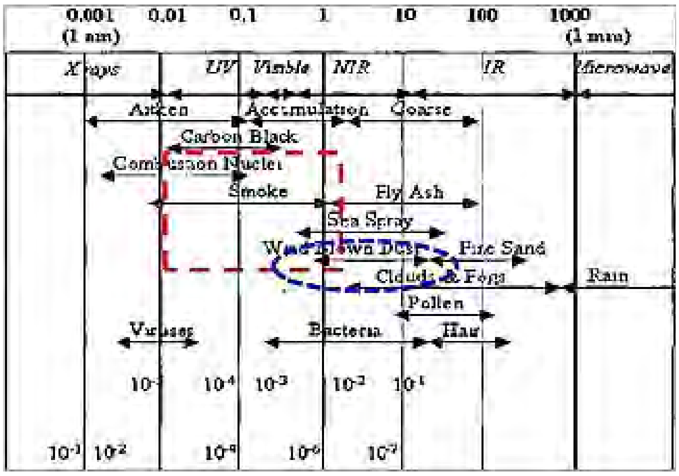

**Fig. 2** Aerosol size characteristics (a) fine mode (small size) (b) coarse mode (big size) found during year 2007 to 2012 from AERONET station at Chiang Mai.

**Table 3** Fine mode and coarse mode AOT in different seasons based on AERONET station during 2007 to 2012.

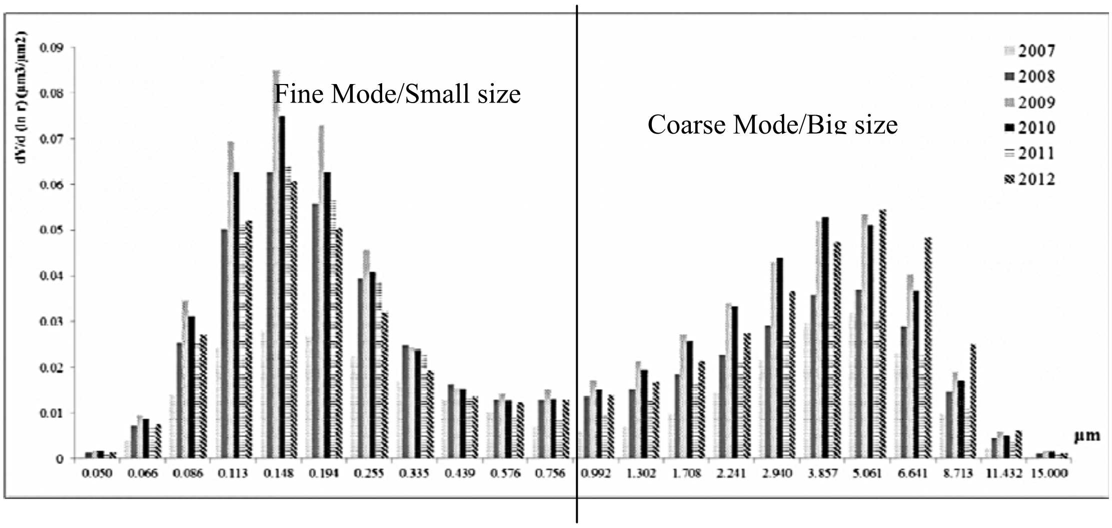
| | **Fine Mode AOT** | | | **Coarse Mode AOT** | | |
|---|---|---|---|---|---|---|
| **Year** | **Pre-Monsoon** | **Rainy season** | **Winter season** | **Pre-Monsoon** | **Rainy season** | **Winter season** |
| 2008 | 0.666 | 0.153 | 0.293 | 0.097 | 0.329 | 0.051 |
| 2009 | 0.763 | 0.128 | 0.333 | 0.103 | 0.230 | 0.050 |
| 2010 | 0.832 | 0.142 | 0.294 | 0.110 | 0.260 | 0.049 |
| 2011 | 0.519 | 0.132 | 0.344 | 0.069 | 0.199 | 0.039 |
| 2012 | 1.088 | 0.178 | 0.211 | 0.074 | 0.184 | 0.035 |

3.1.4 Aerosol types and aerosol sources classification

In Northern Thailand, annual aerosol size distribution shows a bimodal distribution with a fine mode peak at 0.14 micron and coarse mode peak near 5 micron (Fig. 3b). This distribution agreed with Gautam et al. (2012) who found the bimodal distribution in pre-monsoon small aerosol emission from urban and agricultural area over Indochina zone. When compared Fig. 3a with the diagram as shown in Fig. 3a by Jaenicke (1993), it is found that small aerosol particles were about 0.08-0.5 microns similar ranges of Black carbon size and smoke particles. Then, big size of aerosol were about 1.3-8.7 microns could be emitted from sea spray, pollen, fly ash, cloud droplet and rain droplet (Fig. 3a).




(a) Aerosol size distribution by Jaenicke (1993).




(b) Annual mean aerosol optical depths (AOD) over AERONET station from 2007 to 2012.

**Fig. 3** Comparing aerosol size distribution by Jaenicke (1993) and aerosol particles size distribution observed over AERONET station during 2007 to 2012.

When considering the size distribution of the chemical composition from the study of Li et al. (2013) described the basic elements that come from the soil such as $Ca^{2+}$, $Na^{+}$ and $Mg^{2+}$ were found in coarse aerosols or large aerosols particle (Fig. 4). It also found that $K^{+}$ was found prominently in small aerosols particle and were released from biomass burning. Source of Potassium in rainfall was aerosols from sea salt, biomass burning and fertilizer production processes. O'Neill (1993) stated that in the seawater intake Potassium 0.39 g $dm^{-3}$, it ranked 4th of available cations in sea. Berner and Berner (1996) stated that the source of Potassium in the atmosphere above the ground emitted from five sources, namely: 1) the melting of dust 2) fertilizer containing Potassium in soil 3) pollens and seeds 4) biogenic aerosols and 5) forest fires that the major problems in the tropics. Basing on Fig. 3b and Fig. 4 it could be assumed that small aerosols which were in the range of 0.08 to 0.5, it may be the main component is a water-soluble $K^{+}$ which comes from the burning of biomass and may be compounds with $SO_4^{2-}$ was suspended in the atmosphere about 5-12 days and spread to far up to 1,000 kilometers or $NH_4^+$ compounds can float in the atmosphere about 6 days and fly as far as 5,000 kilometers, mostly resulting from the burning coal or fuel.

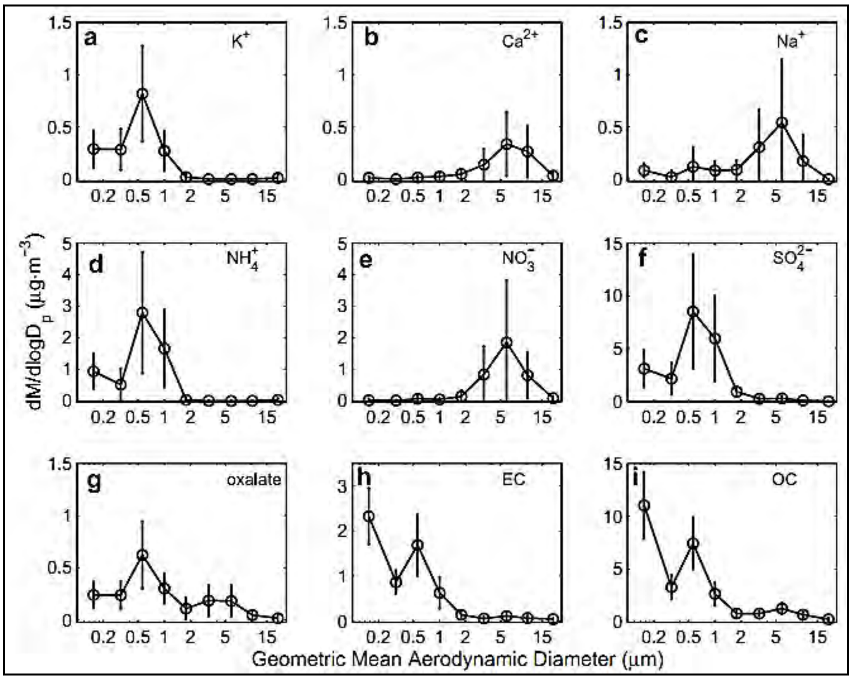



**Fig. 4** The average size distributions of different species. Source: Li et al. (2013).

3.1.5 Hotspot variation for defining burning aerosol

Mean hotspot numbers in Northern Thailand were detected by MODIS during year 2003 to 2012 appeared at about 675 points. The highest hotspot number in year 2007 was found especially in Mae Hong Son. Table 4 shows the highest frequency of hotspot number appearing in March. The highest biomass burning was occurred in 2004 but dramatically reduced in year 2011 because of policy about biomass burning events reducing.

**Table 4** Average monthly Hotspot (HP) during 2003 to 2012 in the different provinces (analyzed based on MODIS data).

| | **Average monthly hotspot (HP) during 2003 to 2012** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Province** | **Jan** | **Feb** | **Mar** | **Apr** | **May** | **Jun** | **Jul** | **Aug** | **Sep** | **Oct** | **Nov** | **Dec** |
| Mae Hong Son | 14 | 235 | 1472 | 589 | 5 | 1 | 1 | 0 | 0 | 1 | 1 | 8 |
| Chiang Mai | 58 | 421 | 1227 | 356 | 7 | 1 | 0 | 1 | 1 | 1 | 5 | 46 |
| Lamphun | 49 | 201 | 136 | 12 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 8 |
| Chiang Rai | 81 | 286 | 797 | 263 | 6 | 1 | 1 | 1 | 2 | 1 | 5 | 59 |
| Lampang | 68 | 294 | 337 | 58 | 3 | 2 | 1 | 1 | 1 | 1 | 4 | 22 |
| Phayao | 36 | 108 | 226 | 79 | 4 | 1 | 1 | 0 | 0 | 1 | 1 | 18 |
| Phrae | 27 | 158 | 317 | 89 | 5 | 1 | 1 | 0 | 1 | 1 | 3 | 33 |
| Nan | 17 | 241 | 1352 | 331 | 5 | 1 | 0 | 0 | 1 | 0 | 3 | 7 |
| Uttaradit | 58 | 139 | 211 | 74 | 10 | 1 | 1 | 1 | 1 | 2 | 20 | 77 |

## 3.2 Variation of cloud and rainfall in upper Northern Thailand

### 3.2.1 Clouds water content (CWC)

Cloud water content (CWC) can be expressed either in g/m$^3$ or mm. Monthly cloud water content during year 2003 to 2012 in the Northern Thailand (Table 5a) indicated the highest CWC in August with 196g/m$^3$. There was high fluctuation of CWC in February and Mar. Cloud water content anomalies in March and April were subnormal at about -2.58 and -1.66 respectively. It corresponded with highest AOT in the same period.

**Table 5** Average monthly Cloud Water Content (CWC), average monthly Cloud Fraction (CF) and average monthly rainfall (RF) during 2003 to 2012 analyzed based on MODIS and TRMMM data.

**(a) Cloud Water Content (CWC); g/cm$^2$**

| Province | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mae Hong Son | 149.7 | 112.8 | 98.9 | 153.4 | 168.0 | 175.4 | 195.7 | 196.1 | 162.5 | 148.8 | 165.6 | 89.0 |
| Chiang Mai | 130.2 | 104.8 | 103.2 | 193.8 | 200.2 | 182.9 | 208.2 | 208.8 | 190.7 | 196.0 | 125.3 | 100.7 |
| Lamphun | 156.4 | 146.2 | 109.5 | 192.5 | 211.8 | 165.6 | 164.0 | 175.8 | 198.8 | 189.2 | 166.3 | 80.1 |
| Chiang Rai | 145.8 | 83.2 | 124.7 | 119.8 | 173.8 | 186.1 | 192.5 | 202.3 | 196.9 | 140.6 | 116.7 | 82.3 |
| Lampang | 80.5 | 108.4 | 112.5 | 114.5 | 179.6 | 143.7 | 166.7 | 183.6 | 174.2 | 195.6 | 106.5 | 71.9 |
| Phayao | 150.1 | 87.6 | 95.4 | 136.7 | 194.0 | 192.0 | 210.5 | 225.7 | 235.3 | 158.6 | 124.9 | 103.6 |
| Phrae | 101.6 | 98.9 | 161.9 | 105.4 | 172.2 | 168.7 | 207.9 | 220.1 | 212.8 | 165.0 | 147.2 | 86.6 |
| Nan | 115.5 | 135.1 | 95.5 | 125.6 | 191.6 | 156.1 | 168.7 | 178.9 | 186.9 | 190.7 | 118.2 | 113.6 |
| Uttaradit | 78.7 | 76.6 | 119.9 | 141.7 | 163.4 | 154.7 | 151.6 | 172.8 | 170.1 | 205.5 | 102.4 | 82.7 |

**(b) Cloud Fraction (CF)**

| Province | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mae Hong Son | 0.12 | 0.10 | 0.26 | 0.46 | 0.62 | 0.68 | 0.68 | 0.68 | 0.64 | 0.43 | 0.22 | 0.16 |
| Chiang Mai | 0.12 | 0.13 | 0.27 | 0.43 | 0.62 | 0.68 | 0.68 | 0.68 | 0.63 | 0.48 | 0.28 | 0.20 |
| Lamphun | 0.12 | 0.15 | 0.28 | 0.51 | 0.68 | 0.72 | 0.70 | 0.68 | 0.64 | 0.49 | 0.28 | 0.21 |
| Chiang Rai | 0.20 | 0.28 | 0.44 | 0.62 | 0.68 | 0.68 | 0.69 | 0.67 | 0.59 | 0.44 | 0.26 | 0.19 |
| Lampang | 0.20 | 0.32 | 0.44 | 0.61 | 0.70 | 0.72 | 0.68 | 0.68 | 0.61 | 0.47 | 0.27 | 0.19 |
| Phayao | 0.18 | 0.23 | 0.39 | 0.53 | 0.64 | 0.71 | 0.69 | 0.68 | 0.60 | 0.45 | 0.26 | 0.21 |
| Phrae | 0.23 | 0.25 | 0.40 | 0.59 | 0.68 | 0.68 | 0.70 | 0.68 | 0.61 | 0.49 | 0.29 | 0.24 |
| Nan | 0.16 | 0.20 | 0.32 | 0.50 | 0.65 | 0.73 | 0.69 | 0.67 | 0.64 | 0.49 | 0.29 | 0.21 |
| Uttaradit | 0.21 | 0.29 | 0.39 | 0.64 | 0.71 | 0.75 | 0.68 | 0.67 | 0.63 | 0.54 | 0.33 | 0.22 |

**(c) Rainfall amount (RF)**

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mae Hong Son | 11.57 | 3.29 | 29.84 | 74.70 | 236.39 | 285.16 | 326.79 | 344.10 | 301.84 | 166.24 | 32.03 | 10.42 |
| Chiang Mai | 12.70 | 5.17 | 34.68 | 90.73 | 229.83 | 224.41 | 262.00 | 288.77 | 299.22 | 146.65 | 28.87 | 10.97 |
| Lamphun | 9.03 | 5.52 | 35.22 | 82.35 | 228.08 | 208.86 | 204.95 | 253.10 | 290.43 | 137.77 | 27.92 | 8.82 |
| Chiang Rai | 16.31 | 12.31 | 53.75 | 145.05 | 226.27 | 222.17 | 281.51 | 351.05 | 302.81 | 98.28 | 24.78 | 11.35 |
| Lampang | 11.27 | 11.21 | 40.75 | 110.62 | 235.38 | 238.83 | 219.80 | 268.72 | 308.34 | 119.13 | 21.02 | 9.25 |
| Phayao | 17.60 | 12.59 | 51.80 | 134.63 | 240.76 | 209.55 | 323.12 | 353.51 | 336.08 | 138.51 | 31.85 | 15.05 |
| Phrae | 17.50 | 11.23 | 53.79 | 133.26 | 232.62 | 203.90 | 288.47 | 345.16 | 325.92 | 131.63 | 29.92 | 11.44 |
| Nan | 10.64 | 8.43 | 41.03 | 104.65 | 232.00 | 182.86 | 203.48 | 254.99 | 304.79 | 128.46 | 27.42 | 10.31 |
| Uttaradit | 10.96 | 10.27 | 39.84 | 107.64 | 242.38 | 203.21 | 195.71 | 240.92 | 303.30 | 115.50 | 23.99 | 9.68 |

3.2.2 Cloud cover or Cloud fraction

All the clouds that covered the sky visible to the eye were in the range of 0-1. It was found that cloud covered in the upper northern Thailand were maximum in June at about 0.71 or 71% of the sky areas, especially over Uttaradit. Minimum clouds covered were found in January at about 0.12 or 12% especially in Mae Hong Son, Chiang Mai and Lamphun (Table 5b).

3.2.3 Rainfall amount

In the Northern Thailand, average annual rainfall amount was approximately 1,661 mm and average monthly rainfall was highest in August about 300 mm especially in Phayao and Phrae (Table 5c).

**3.3 Relationship between aerosols, cloud and rainfall**

The relationship between aerosols, clouds and rainfall based on Aerosol Optical Thickness (AOT) Clouds Water Content (CWC), Clouds Fraction (CF), Rainfall (R) and Hotspot number (HP) using multiple correlation and multiple regression analysis are the details as follows;

3.3.1 Relationships between aerosols, cloud and rainfall using Multiple Correlation

Multiple correlation analyzed relationships between two parameters based on Correlation Coefficient (Cohen, 1988). It could be indicated that Rainfall (R) was high positive relationship with Clouds Fraction (CF) and Clouds Water Content (CWC). In the other hand, rainfall amount was high negative relationship with Aerosol Optical Thickness (AOT) and Hotspot (HP) (Table 6). In Chiang Mai, Mae Hong Son, Lamphun and Uttaradit, rainfall amount was mostly related with Clouds Fraction (r=0.359 to 0.508). In Chiang Rai, Lampang, Phayao, Phrae and Nan, it was found that the rainfall amount (R) was most closely associated with Clouds Water Content (r = 0.284 to 0.639).

**Table 6** Pearson correlation coefficient for Aerosol Optical Thickness (AOT), cloud fraction (CF), rainfall, cloud water content (CWC) and hotspot (HP) factors during 2003 to 2012.

| Province | Factors | Cloud Fraction | Rainfall | CWC | AOT | Hotspot |
|---|---|---|---|---|---|---|
| Chiang Mai | Cloud Fraction | 1 | .474** | .382** | -.117 | -.216* |
| | Rainfall | .474** | 1 | .471** | -.354** | -.385** |
| | CWC | .382** | .471** | 1 | -.125 | -.254** |
| | AOT | -.117 | -.354** | -.125 | 1 | .724** |
| | Hotspot | -.216* | -.385** | -.254** | .724** | 1 |
| Mae Hong Son | Cloud Fraction | 1 | .508** | .224* | -0.133 | -0.152 |
| | Rainfall | .508** | 1 | .320** | -.471** | -.349** |
| | CWC | .224* | .320** | 1 | -.229* | -.214* |
| | AOT | -0.133 | -.471** | -.229* | 1 | .733** |
| | Hotspot | -0.152 | -.349** | -.214* | .733** | 1 |
| **Province** | **Factors** | **Cloud Fraction** | **Rainfall** | **CWC** | **AOT** | **Hotspot** |
| Chiang Rai | Cloud Fraction | 1 | .417** | .325** | .026 | -.098 |
| | Rainfall | .417** | 1 | .599** | -.331** | -.355** |
| | CWC | .325** | .599** | 1 | -.266** | -.296** |
| | AOT | .026 | -.331** | -.266** | 1 | .803** |
| | Hotspot | -.098 | -.355** | -.296** | .803** | 1 |
| Lamphun | Cloud Fraction | 1 | .456** | .183 | -.061 | -.317** |
| | Rainfall | .456** | 1 | .284** | -.324** | -.429** |
| | CWC | .183 | .284** | 1 | -.058 | -.235* |

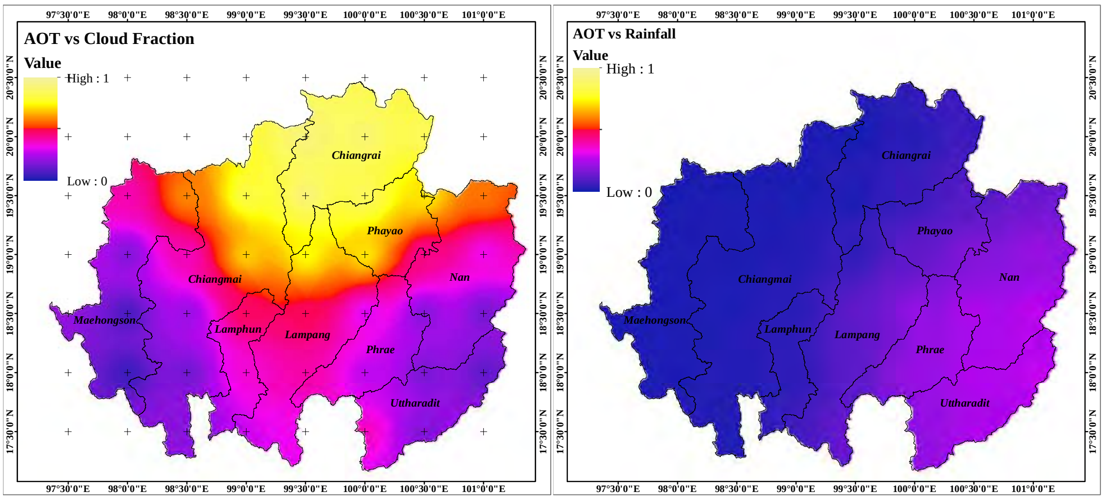
| | | | | | | |
|---|---|---|---|---|---|---|
| | AOT | -.061 | -.324** | -.058 | 1 | .441** |
| | Hotspot | -.317** | -.429** | -.235* | .441** | 1 |
| Lampang | Cloud Fraction | 1 | .399** | .329** | -.017 | -.155 |
| | Rainfall | .399** | 1 | .548** | -.389** | -.443** |
| | CWC | .329** | .548** | 1 | -.174 | -.244** |
| | AOT | -.017 | -.389** | -.174 | 1 | .654** |
| | Hotspot | -.155 | -.443** | -.244** | .654** | 1 |
| Phayao | Cloud Fraction | 1 | .463** | .348** | .021 | -.153 |
| | Rainfall | .463** | 1 | .639** | -.261** | -.402** |
| | CWC | .348** | .639** | 1 | -.317** | -.497** |
| | AOT | .021 | -.261** | -.317** | 1 | .713** |
| | Hotspot | -.153 | -.402** | -.497** | .713** | 1 |
| Phrae | Cloud Fraction | 1 | .437** | .286** | -.152 | -.157 |
| | Rainfall | .437** | 1 | .528** | -.413** | -.406** |
| | CWC | .286** | .528** | 1 | -.320** | -.196* |
| | AOT | -.152 | -.413** | -.320** | 1 | .728** |
| | Hotspot | -.157 | -.406** | -.196* | .728** | 1 |
| Nan | Cloud Fraction | 1 | .430** | .307** | -.119 | -.132 |
| | Rainfall | .430** | 1 | .454** | -.362** | -.284** |
| | CWC | .307** | .454** | 1 | -.294** | -.337** |
| | AOT | -.119 | -.362** | -.294** | 1 | .783** |
| | Hotspot | -.132 | -.284** | -.337** | .783** | 1 |
| Uttaradit | Cloud Fraction | 1 | .359** | .181 | -.061 | -.268** |
| | Rainfall | .359** | 1 | .353** | -.418** | -.511** |
| | CWC | .181 | .353** | 1 | -.109 | -.237* |
| | AOT | -.061 | -.418** | -.109 | 1 | .731** |
| | Hotspot | -.268** | -.511** | -.237* | .731** | 1 |

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

AOT = Aerosol Optical Thickness (unitless)
R = rainfall amount (mm)
Hot = hotspot (point)
CF = cloud fraction (unitless)
CWC = cloud water content ($g/cm^2$)

Fig. 5a showed the spatial correlation between average annual AOT and annual cloud fraction. It was noticed that there were high correlations between AOT and cloud fraction over Chiang Rai, some area in Phayao and Chiang Mai. In the other hand, spatial correlation between AOT and rainfall amount showed low.




(a) (b)

**Fig. 5** Spatial correlation of (a) average annual AOT and cloud fraction and (b) average annual AOT and rainfall in Northern Thailand.

3.3.2 Relationship equations between aerosols, cloud and rainfall using multiple regression analysis

The interaction between aerosol and rainfall amount is shown in Table 6. When there was less aerosol amount (less AOT), rainfall amount would be high. In the other hand, the highest AOT in dry season would cause the less rainfall. It was found that there were many factors influencing cloud and rainfall amount rather than aerosol concentration. So, in order to get better relationships between aerosol with cloud and rainfall, one should consider including the other criteria (i.e., relative humidity, polluted cloud, atmospheric stability, etc.).

Results of the stepwise multiple regression analysis to select the factors influencing the average monthly rainfall indicated that in almost all cloud water content (CWC) and cloud cover influence on increasing rainfall as CWC and Cloud cover are also a contributory factor to increase water droplets in clouds, including increased reflectivity in cloud. On contrary, aerosols effect on the rainfall decline was exception in Phayao Province where the AOT was also high. This increase may be due to other factors such as weather conditions played more influence than the aerosol factor. In general, all relationship equations indicated variability of aerosol and cloud could be moderately explained changing of rainfall (Table 7).

**Table 7** Relationships between AOT, cloud water content, cloud fraction and rainfall amount using multiple regressions.

| **Province** | **Equations (Relationships)** | r |
|---|---|---|
| Mae Hong Son | R = 124.92 -297.323AOT+167.671CF | 0.636 |
| Chiang Mai | R = 41.086 +0.469CWC -171.315AOT+105.994CF | 0.625 |
| Chiang Rai | R = -7.269 +0.873CWC -111.503AOT+106.352CF | 0.675 |
| Phrae | R = 35.112 +0.016CWC -169.391AOT+107.556CF | 0.643 |
| Phayao | R = -47.78 +0.958CWC +107.89CF | 0.688 |
| Uttaradit | R = 91.034 +0.325CWC -219.898AOT+86.67CF | 0.578 |
| Nan | R = 33.678 +0.480CWC -108.367AOT+97.083CF | 0.580 |
| Lampang | R = 24.988 +0.765CWC -185.200AOT+86.136CF | 0.665 |
| Lamphun | R = 77.378 +0.100CWC -195.406AOT+117.317CF | 0.537 |

AOT = Aerosol Optical Thickness (unitless); R = rainfall amount (mm)
CF = cloud fraction (unitless); CWC = cloud water content (g/cm$^2$)

## 4 Conclusions

In Northern Thailand, it was found that almost all provinces showed the highest average annual AOT in March especially over Chiang Rai with 0.79. Fine mode of aerosol (small size) could be dominated in dry period. While the big size of aerosol was dominated in wet period. In dry season, black carbon from on-site biomass burning were the main types of aerosol, which they actually affected on cloud and rainfall in early rainy season.

Cloud water content anomaly show that in March and April are subnormal at about -2.576 g/m$^3$ and -1.658 g/m$^3$ respectively. It corresponds with highest AOT in the same period in the Northern Thailand. Average monthly rainfall amount in the Northern Thailand showed the highest amount in September with 308.08 mm Aerosol concentration was high effect on decreasing cloud and rainfall in dry season, but it showed that the size of aerosols play more influence than aerosol concentration in rainy season because there was high water vapors in the atmosphere. In the Northern Thailand, there was moderate relationship between rainfall amount with AOT and Cloud Fraction (CF). It could be said that increased aerosol loading induced to decrease rainfall amount.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